

Three-Dimensional Imaging for Orthodontics and Maxillofacial Surgery

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Preface

When we embarked on this project, we appreciated that a wide range of disciplines would be involved in developing acquisition systems and software analysis packages for a host of applications for medical, medically allied, entertainment, and military/security groups. In fact, three-dimensional imaging potentially is of interest to all and certainly has the potential to have an impact on everyone in daily life.

We took a clear initiative to build a text that is not only informative, illustrative, and applied, but also provides the latest in state-of-the-art technology. The book is set out in three sections – (1) diagnostic and assessment methods, (2) applications, physiological development, and surgical procedures, and (3) movement and facial dynamics – to cover clinical interest in the craniofacial complex not only for dentists, specialists, and specialties related to dentistry, but also for other professions that deal with the craniofacial complex, such as speech therapists and psychologists.

We have chosen a group of authors world-renowned in their field, and their topics cover a wide range of applications representing different levels of sophistication, experience, and knowledge. The chapters are well illustrated to facilitate knowledge and skills transfer. Each chapter is well referenced to enable interested readers to facilitate their understanding and build a foundation of knowledge. Certain chapters direct readers to utilize open-sourced, readily available software, commercially available packages, and also the mathematical theory behind problem-solving.

This book addresses a gap in the applications of three-dimensional imaging in dentistry and allied health professionals. We hope that we have derived a blend of topics that will be of interest to the novice as well as to experts in different disciplines.

Stephen Richmond
Chung How Kau

Part 1

Imaging, Diagnostic, and Assessment Methods

1 The Legalities of Cone Beam Imaging

*Kenneth Abramovitch, Christos Angelopoulos,
and Randall O. Sorrels*

INTRODUCTION

When a patient requires an imaging procedure, there are several underlying scenarios that are part of the process. These events have a complicity of legal implications. The legal implications may vary from one jurisdiction to another, regardless of whether one is referring to national, state/provincial, county/parish, city, or municipality. The intent here is to describe legal processes that can establish guidelines consistent with good quality healthcare delivery.

Imaging procedures are required to evaluate the presence or absence of a disease state or to perform the craniofacial morphometric analyses necessary to develop dentoalveolar and craniofacial treatment plans. The latter are frequently indicated to evaluate craniofacial esthetic and functional relationships.

The indications for a cone beam computed tomography (CBCT) scan are usually associated with some degree of morbidity, hence there is an element of risk associated with either performing or abstaining from the procedure. These associated risks may be from either the physical harm from the procedure, the potential morbidity of a misdiagnosis, or the potential morbidity from a failure to diagnose. Physical harm from imaging procedures is related to the harmful biologic effects of ionizing radiations. These risks are very low and are discussed in another chapter. Legal issues associated with misdiagnosis and a failure to diagnose, as well as disclosure and informed consent and adequate documentation, are discussed here.

EDUCATION AND TRAINING

The utilization of any diagnostic procedure, including cone beam imaging, should be ordered and performed based on a sound knowledge of the potential diagnostic yield of the procedure. Due to the

increased popularity of and excitement generated by this imaging modality, cone beam imaging is often thought of as the “gold standard” for craniofacial imaging. It is expected by novices to provide a solution to every diagnostic need. As with every diagnostic procedure that may be potentially harmful, cone beam scans should be ordered and performed when there is justification that the benefits of the examination outweigh the possible risks (European Academy of Dento-Maxillofacial Radiology). It is the duty of the oral health professional to be educated as to the diagnostic potential and to the possible benefits as well as risks of this technology.^{1,2}

The auxiliary personnel involved in all the stages of image acquisition (patient referrals, patient history, patient preparation, image acquisition, and data-handling) must have received the appropriate education and training for proper technique and for radiation safety and protection measures for the patient as well as for the operators. Similarly, training is imperative for the dental professionals who will utilize the acquired data. Proper image selection for the diagnostic task at hand and proper reconstructions in order to yield the required information is frequently the result of training and experience together. CBCT is becoming part of the routine curriculum in most accredited graduate dental programs. Accredited continuing education courses are also available to practicing clinicians. These courses are readily found through routine Internet-based search engines. An example of one resource is listed in the reference section.³

DISCLOSURE AND INFORMED CONSENT

When an imaging procedure is requested for a patient, the patient must be given specific information about the procedure. The legal process of informing a patient about the medical procedure is referred to as *disclosure*. The patient is informed of the imaging procedure indicated and then the need and benefits associated with the procedure. The patient must also be informed of any harm or side effects from the procedure (biologic harm), as well as the risks associated if a disease is not diagnosed because the procedure is not performed or the patient refuses the procedure. The patient must also be informed of other possible diagnostic tests or alternate diagnostic procedures that may be available instead of the imaging procedure, for example ultrasound, standard computed tomography, serum analysis, etc. Patients must also be permitted to ask additional questions to clarify their understanding of the information that has been presented.

If this degree of disclosure has been performed, the patient has been presented with adequate information to be better informed to make a decision on whether or not to give his or her consent for the imaging procedure. The process of informing the patient with this degree of information is the knowledge base necessary for a patient to give *informed consent*. The components of informed consent are summarized in Box 1.1.

Box 1.1 Summary of inclusions necessary for the process of informed consent

- a. the imaging procedure and the purpose of the procedure
- b. potential benefits of the procedure
- c. risks to the patient's health if the procedure is performed
- d. risks to the patient's health if the procedure is **not** performed
- e. opportunity for the patient, legal guardian or trustee to ask for additional information or for clarifications

From Iannucci and Howerton.¹⁹

Box 1.2 Factors that contribute to negligence with informed consent

- a. lack of patient (legal guardian or trustee) consent
- b. consent from a minor
- c. consent from an inappropriate (illegal) guardian
- d. consent from an individual under emotional duress or under the influence of drugs or alcohol
- e. consent based on fraudulent or incorrect statements
- f. disclosure from unqualified (non-licensed) personnel

From Iannucci and Howerton.¹⁹

The basic tenet of informed consent is that the clinician supplies adequate medical and dental knowledge necessary for the patient to make an intelligent decision on whether or not to undergo the recommended imaging procedure. Since the written documentation of this process should be in the patient's record, this is best achieved with a written consent form. The informed consent (if given) is confirmed with the patient's signature and is often also signed by at least one witness. This consent often serves as a legal document if it contains disclosure and is obtained freely.

After an appropriate disclosure, a patient may decide to decline the procedure. In such instances, the clinician's ability to treat the patient may be compromised. If the dentist's treatment will be compromised by the lack of essential diagnostic data, the patient should be so informed. In these situations where the "untrained" patient dictates the course of the diagnostic workup and treatment and this limits the diagnostic ability of the clinician, it is often best to terminate further professional interaction.

NEGLIGENCE AND MALPRACTICE

Procedures performed on a patient without their consent is not considered good practice, that is, is negligent behavior, and is susceptible to a legal claim of malpractice. Negligence in most jurisdictions means the failure of a healthcare provider to act as an ordinary reasonable healthcare provider would act in the same or similar circumstances. This means that the act or action taken would not be performed by a reasonable clinician. In litigation scenarios, negligence may also mean failing to do something that a reasonable clinician would *not* do in a similar situation.

Although it may be subject to legal and professional opinion, there are several situations in which negligence can be legally determined. These situations are outlined in Box 1.2. Each situation is subject to legal and professional opinion before the decision of negligence is made.

WRITTEN DOCUMENTATION FOR AN IMAGING SCAN

"Do it right – write it down" and "If it's not in the record – it did not occur" are popular axioms that serve as guiding principles for dentists and other healthcare professionals to minimize professional risks.

In keeping with the rationale and need for a patient record, the written record preserves the memory of the patient–clinician interactions (treatments or discussions) that have occurred. This written record can be used to share protected health information. These records are also permissible for legal proceedings in the event that there is litigation. But proper documentation protects the treating clinician.

It is recommended that a standard entry in a patient record for an imaging procedure should include the patient's informed consent and the specific imaging strategies and reconstructions utilized

to investigate the diagnostic task. The imaging procedure should have some documentation of the exposure settings, that is, kilovolt and milliamperè values, and seconds of exposure or scan sequence. In many instances, a review of the scan sequence will disclose these aforementioned technical parameters. The size of the area exposed, that is, the field of view, should also be included. This exposure information is required in the record in the event that effective dose or dose equivalence needs to be calculated for a specific procedure.

The types of image reconstruction and the software utilized for the reconstructions should be included to demonstrate the steps followed and the views evaluated in arriving at professional decisions and diagnoses. In the event that one had to replicate these reconstruction data to see how diagnoses or decisions on treatment planning were made, the sequence steps would be available in the record. This information is also helpful in the event that the imaging strategy does not provide the diagnostic information necessary. With this imaging history, the treating or consulting clinician can develop other imaging strategies (software reconstructions, software programs, or different imaging acquisitions) to address the diagnostic task at hand.

DOCUMENTATION OF DIAGNOSTIC FINDINGS

Most regulatory agencies stipulate that there must be an entry in the record reporting the diagnostic information obtained from the imaging procedure. This entry is usually complementary to the clinical indication for the procedures in the informed consent, for example reporting morphometric data for an edentulous ridge site prior to dental implant surgery.

If a patient is referred for an implant evaluation, it is understood that the focused area of the implant receptor sites and possibly bone graft donor sites will be evaluated. Hence if an area of edentulous ridge will be used as a receptor site for an implant placement, the selection site should be identified, along with the reasons why. However, it is not acceptable to merely report these findings and not document other significant information, that is, disease that may affect the patient's long-term prognosis.

In another instance, a CBCT scan may be requested to evaluate pathology around an impacted mandibular third molar, but there may be other disease processes in the jaws that are within the field of view imaged. This latter would include a number of possible entities involving the orbits, paranasal sinuses, and scanned cranial and cervical areas. Multiple reportable findings are noted on CBCT scans.^{4,5} Hence, it is not acceptable to avoid the rest of the dataset. There is probable liability for failing to diagnose conditions in the entire dataset of the CBCT scan. If a significant finding is missed, and this causes harm to the patient, the referring clinician and even the imaging facility (if it is not the patient's treating clinician) may be liable for being negligent.

The entire dataset in all planes of view needs to be viewed, and any abnormalities must be reported. In cases with positive findings, appropriate referrals may be further indicated. If the imaging facility or the referring clinicians are not able to review the data, there are dental and or medical radiology reporting services that can perform these services. This process can minimize liability from failing to report pathology and referring it in a timely manner.⁶

WAIVERS FOR IMAGING LIABILITY

It is fairly standard in dental education that dentists receive training in reading two-dimensional images of the dentoalveolar structures and adjacent anatomy in the head and neck region on bitewing, periapical,

panoramic, and skull cephalograms (lateral and posteroanterior). However, most dentists are not trained to interpret the multiangle and three-dimensional (3D) projections obtained from cone beam scanners and the related software imaging. It has been suggested that patients can sign waivers of liability for disease that may be present in the scan data. The reasoning for the liability waiver is because it is not a disease that the clinician is specifically investigating or is not within a dental clinician's training or expertise.⁷

However, liability cannot be signed off by a patient. Statutes, legal opinions, and malpractice insurance companies have stepped forward to negate the legitimacy of this waiver of liability. Both the referring/treating clinician and the imaging facility have a legal obligation to assure that the entire dataset is reviewed and that potential conditions not in the areas specifically reviewed by a referring doctor are reported.⁸

A patient is not as knowledgeable to assess the risk-benefit analysis for the necessity to have a scan read. Dental clinicians are more knowledgeable than patients concerning the incidence, pathophysiology, and recognition of diseases in the jaws. Hence the patient is not as knowledgeable to assess the same risks and make a reasoned opinion on whether or not to overlook interpreting the data. In the event that an occult lesion is noticed at a later date but was found to be present in the data of a cone beam scan ordered for dental treatment, there is a strong likelihood that the dentist will be liable for failure to diagnose. The dentist has more expertise than the patient to recognize the disease process, and hence should not have left the decision to interpret all the data with the patient. The doctor is liable in the event that a disease process is detected.^{8,9}

Because of the potential harm to patients from failing to report on all the data in a CBCT scan, professional organizations have prepared recommendations and guidelines that pertain to the need for formal written interpretation reports in the patient's record based on a review of the entire CBCT dataset.^{1,2,10,11} The treating or consulting clinician must review the entire dataset and interpret the significance of the findings. Since interpreting advanced images is not a standard curricular subject in accredited teaching institutions, most dentists do not have this training. If a dentist without advanced training assumes the responsibility of reading the data, he is accepting a greater duty to the patient than he or she may be prepared for. If an occult disease is missed, the clinicians have breached this greater duty that they assumed, and this may be considered to be an act of professional negligence.

The data must be read by a trained clinician. Oral and maxillofacial radiologists have acquired this knowledge in advanced training programs. Although the data do not have to be read by a trained oral and maxillofacial radiologist, the clinician reporting and interpreting the data must demonstrate equivalent skills.¹ In the advent of litigation where a provider was negligent in evaluating pathology from a CBCT scan they had ordered, the creditability of the clinician's diagnosis or lack of a diagnosis will be compared with the credentials of a certified OMR (Oral and Maxillofacial Radiology practitioner). In a court of law, the clinician may be culpable of inappropriate care. If a dentist does not have a level of equivalent training, it is best to send the data to qualified services.^{1,2,10,12,13}

It is anticipated that, in the future, it will become common to find imaging clinics staffed with oral and maxillofacial radiologists to respond to the imaging needs of the profession. The range of services is likely to include assisting with image acquisition, interpretation, and conversion of the data to the multitude of two-dimensional and 3D imaging software programs.¹⁴

This issue remains highly controversial. Some attorneys are of the opinion that if the subject matter is not part of the standard dental school curriculum, dentists are not trained to make a diagnosis beyond the level of their training.⁷ However, it becomes a clinician's responsibility to seek this information from other disciplines of expertise in the profession, that is, the OMR.

A similar analogy exists in the case of surgery to remove an oral lesion. A sessile nodular growth presenting in the floor of the mouth may appear to be a benign squamous papilloma or a fibrous hyperplasia (fibroma). However, the histologic diagnosis based on the types and arrangement of the cells may actually be a verrucous or squamous cell carcinoma. The histologic diagnosis is imperative to properly manage the case. This diagnosis is made by a certified Oral Maxillofacial Pathology practitioner (OMP). It would be indefensible for the treating clinician either to overlook the lesion or to remove it on the provision that it is a benign lesion solely from the clinical findings. Furthermore, if a histologic diagnosis is made, it would be made with the expertise of an OMP.

STORAGE FORMATS AND CONFIDENTIALITY

There are many different acquisition and reconstruction softwares available with the various cone beam scanning units. This actually has the potential to be a deterrent to quality patient care as healthcare providers cannot reasonably be expected to keep an inventory of all of the proprietary softwares to manage digital image files.

In response to this dilemma, industry, government, and professional organizations assembled over several sessions as the International Standards Organization (ISO) to develop a standard imaging file format for file transfers, the Digital Imaging and Communications in Medicine (i.e., DICOM) standard file format, ISO12052:2006.¹⁵ The DICOM file format is a dynamic standard, being reviewed and modified on a regular basis. Dental input to this process comes from many organizations including dental. The American Dental Association, as a conduit for its various councils and standing committees, has been a member of the DICOM Standard Committee since 1996.¹⁶ The American Dental Association recommended as early as 2000 that dental manufacturers make their files convertible to the DICOM file format. In so doing, manufacturers who do not follow the DICOM standard will not be able to stay viable in a competitive marketplace.^{14,16}

With improved access to utilizing these file formats comes the responsibility of protecting the patient's personal health information. In the United States, there are federal regulations from the federal department of Health and Human Services on the protection of patient personal health information that were initially set forth by the Health Insurance Portability and Accountability Act in 1996.¹⁷ According to the legislation, failure to keep a patient's personal health information confidential on encrypted files or secured file transfer protocols will result in significant penalty. Hence most of the time, the data are transferred via secured websites and networks. The degree of measures necessary to maintain confidentiality is dependent on the size and contents of the image files. Details of these measures are available from other sources.¹⁸

OWNERSHIP

The facility or practice that exposes the patient to X-radiation and acquires the CBCT scan is the rightful owner of the image data, regardless of who actually ordered or paid for the diagnostic procedure.¹⁹ The facility or practice would of course document that the procedure was performed and also establish a protocol to document the diagnostic information acquired from the scan, that is, the interpretation report. Ownership of the data may be transferred at the option of the rightful owner to another practice or facility. However, as previously discussed, proper protection of the patient's personal health information

must be maintained.^{17,18} The rightful owner should also maintain documentation of the details of any records transfer.

Patients maintain the right of access to the information in their health record. This information cannot be withheld from patients. If requested, copies should be provided to the patient or their legal guardian or trustee. If there are costs associated with the duplication, reasonable fees in addition to the original remuneration may be requested.

CONCLUSION

Cone beam imaging has generated remarkable excitement in the dental profession. As with any other diagnostic and treatment modality, its value is greater when properly utilized. Responsibility is the key factor for the utilization of cone beam technology. From proper referrals and patient selection, to diagnostic image acquisition and proper image interpretation, adherence to principles will maximize the yield. In this case, the major principle served is to do the right thing for the patient.

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Three-Dimensional Surface Acquisition Systems for Facial Analysis

Chung How Kau

INTRODUCTION

Surface acquisition systems for facial imaging are improving at a rapid pace as a result of the introduction of sophisticated three-dimensional (3D) devices into the market. These advancements also mean that the soft tissues of the face can be evaluated in a faster, less invasive manner compared with conventional anthropometric techniques.

Although there have been significant investigations in the past on facial skeletal structures, the number of papers focusing on and analyzing soft tissue morphology and growth is comparatively small in relation to the general oral and maxillofacial literature.¹ Yet the external profile is by far the most visible entity that clinicians and lay people perceive, and on which they formulate judgments. In the modern day, with a greater emphasis being placed on the balance between the hard and soft tissues, it is important to have reliable and available data on the external soft tissue profile. Most of the available data on the changing soft tissue profile has been obtained from cephalometric data, with a smaller number of research data being obtained from limited 3D data.

A number of reviews have been written on the use of 3D technology in dentistry and oral maxillofacial surgery.²⁻⁵ This chapter will, however, focus on imaging devices that have been used to capture facial surface morphology, and explore their advantages and disadvantages. A discussion on the applications to medical imaging will also be discussed.

TYPES OF SURFACE ACQUISITION SYSTEM

There are numerous ways of acquiring the facial soft tissue surface. In this chapter, surface imaging devices may be classified in the manner set out in Table 2.1.

Table 2.1 Tabular representation of surface imaging devices

Photogrammetry	Traditional stereo-photogrammetry
Lasers	Fixed units Medical Graphics and Imaging Group, UCL Cyberware Laboratory 3030/SP Others Portable and mobile Minolta Systems (Model 700, 900, 910, 9i) Polhemus hand-held (Fastscan)
Structured light	Single camera Multiple camera Moiré patterns OGIS Range Finder RFX-IV CAM, three-dimensional Shape system C3D-dimensional stereo-photogrammetry (Glasgow) – computer aided 3dMDface system Others
Video-imaging	Motion-Analysis
Radiation sources	Three-dimensional cephalometry Computed tomography scans Cone beam computed tomography
Others	Magnetic resonance imaging Ultrasound

Traditional stereo-photogrammetry

Photogrammetry is the science of measurements of photographs, reconstructs the measurements of two-dimensional or 3D structures from photographic reproductions⁶ and it has been used in medicine and dentistry since the 1940s.⁷ Tanner and Weiner modified and standardized this technique so that certain anthropometric dimensions could be measured to a degree of accuracy similar to direct methods.⁸ Stereo-photogrammetry is a technique that uses two or more cameras configured as a stereo-pair to obtain 3D coordinates of facial morphology. Early photogrammetric methods utilized techniques used by cartographers that incorporated contour mappings with varying subintervals. It was therefore often laborious, tedious, and expensive to map the facial structures in three dimensions.^{9–11} These techniques have also been applied to volumetric analysis and the biostereometric analysis of surgically corrected abnormal faces.^{12,13}

Stereo-photogrammetry, as already explained, refers to combining multiple views of photos to form a 3D image. For the purposes of this chapter, a light pattern projected onto a face will be classified as a structured light system. Beard and Burke introduced a method in 1967 that projected a radial grid onto the face.¹⁴ This gave numerous points of intersecting measurements and correspondence. Two stereometric cameras and a special flash unit mounted between the lens systems were required. Ras and co-

workers^{15,16} described the use of two semi-metric cameras mounted 50cm apart on a frame with a positioned convergence angle of 15 degrees. A flash spot was positioned between the cameras, and a grid was projected onto the face. This grid facilitated the registration of the two photographs to create a perception of depth. These systems were checked for reliability and validity and used for the analysis of patients with cleft lip and palate and facial asymmetry.^{15,17}

Laser scanning

In recent years, laser scanning has become a commonly used technique in acquiring 3D data from objects in the engineering industry.¹⁸ It is a valid and reliable technique that is used to detect minute and microscopic defects in the automotive and aerospace industries.

Laser technology utilizes optical principles and essentially is an active stereoscopic technique in which the distance of the object is computed by means of a directional light source and detector. A laser beam is “deflected” from a mirror onto a scanning object. The resultant deflection angle of the laser beam may be calculated by simple trigonometry. As the laser beam is projected onto the physical object, the beam is scattered, and this is then captured on a detector. The distance between the object and the detector and source can be calculated by geometric principles. The data may be translated into simple x -, y -, z -coordinates.

There are two broad classifications of laser devices for 3D acquisition according to the source of the beam. These are commonly known as singlepoint and slit scanners. Due to the time required to scan the object, as well as the optical and mechanic simplicity, a slit scanner (with a projection of a plane line) is the more practical solution for capturing facial morphology.¹⁸ An example of the principle of laser triangulation and the laser imaging system is shown in Figure 2.1. Other laser imaging devices (time-of-flight systems) are also available but will not be mentioned here.

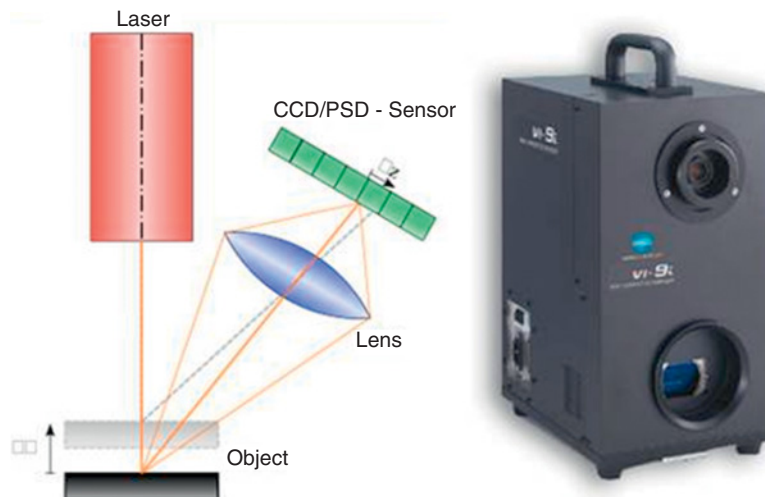


Figure 2.1 Principles of laser triangulation and example of a laser scanning system.

Fixed units

The Medical Graphics Imaging Group system from University College London

Moss and co-workers¹⁹ were one of the first groups to describe the use of lasers in facial imaging. The MGI system (University College London, Malet Place Engineering Building, London, UK) used a low-power helium–neon laser beam that was projected onto the face and viewed from an oblique angle by a television camera. The laser light had a wavelength of 632.8nm and a power not exceeding 1mW. Subjects were scanned every 2.8 degrees of rotation except over the central portion, where 1.4 degrees was used. A total of 20,000 coordinate points were obtained, and the quoted precision was 0.5mm. There was a skin exposure time of less than 10 minutes.¹⁹ This system was independently validated to within 0.9mm²⁰ (over the entire facial surface) and had a 1mm facial morphology reproducibility of adult facial averages.²¹ A variety of applications have been described for this imaging system.

The main problem associated with the technique was the time to complete a scan, which was reported as 20 seconds. Reliability studies to test the reproducibility of facial morphology were carried out on adults, although the number of subjects was small ($n = 10$). Furthermore, all measurements recorded had to be pooled together to form averages in order to make comparisons.

Cyberware Laboratory 3030/SP

This was a commercially available surface laser scanner produced by Cyberware laboratories (Cyberware Inc, California, USA). The Cyberware projected a low-intensity laser onto an object to create a highlighted profile. A high-quality video sensor captured this profile from two viewpoints. The system could digitize thousands of these profiles in a few seconds to capture the shape of the entire object. Simultaneously, a second video sensor acquired color information. The scanner was able to capture 262,144 points each defined by an x -, y -, z - and RGB (red, green, blue) value.

Bush and Antonyshyn reported on the validity of measuring anthropometric landmarks using this device.²² They reported a number of potential errors that could occur:

- motion artifacts
- biologic variation
- inaccuracy in digitization
- poor landmark identification.

However, optimal positions were obtained when the head was in the center of the scanning gantry and with the Frankfort horizontal plane elevated at 10 degrees from the horizontal. Under these conditions, all measured landmarks were visualized ideally and the variance in landmark localization was less than 0.6mm in the x -, y -, and z -axes. Girod and co-workers²³ used the system as a photorealistic surface superimposed onto spiral computed tomography (CT) images. The authors did not, however, report on the accuracy associated with this technique.

In another study, Okada used this method to create facial contours, facial units, and subunits.²⁴ He did so by defining highlights, shadows, and borderlines between the areas based on a technique described by Barnett and Whitaker.²⁵ Another team of researchers, using the same system as a PlayStation® motion platform, measured area and volumetric data on patients with facial swellings.²⁶ Data were then translated to a computer-aided design program in a Microsoft Windows system. Using such software, the midline of the patient's face was set as the symmetry axis, and the reference point symmetry was taken from both sides of the face. The area of the patient's face was calculated with a triangulation mechanism.

Unfortunately, the calculation method was unclear. Guest and co-workers also used the scanner to evaluate methods of superimposing soft tissue changes after orthognathic surgery.²⁷

Other fixed unit lasers

The Surfacer 3D-VMR201 (UNISN Inc, Osaka, Japan) combined 3D reconstructed cephalometric skeletal images and laser-scanned facial images to produce computer-generated models. This preliminary study did not state the accuracy of the system. A research team in China also manufactured a prototype fixed laser system for trials on human subjects.²⁸ The system emitted a standard laser with a wavelength of 650 nm and had a manufacturer's precision of 0.5 mm. The system had a scanning range of 0–180 degrees and a radius of 30 cm. Clinical tests showed acceptable results, but the system had a long scanning time of 1 minute.

Portable and mobile

Minolta laser scanners

In 1997, Minolta (now known globally as Konica Minolta; Minolta Co, Ltd, Osaka, Japan) introduced a series of VI-digitizers and were, according to the manufacturers, "going to revolutionize the way surface imaging was carried out."²⁹ These noncontact systems enabled rapid 3D acquisition that could be used in medical applications that included orthodontics and maxillofacial surgery.

The VI-700 was the first in a series of this generation of digitizers. By triangulating distances between the reflecting laser beam and the scanned surface, the surface laser scanner could detect not only an object's length and width, but also its depth. The reliability of generating 3D object reconstructions was assessed independently in Chicago.³⁰ Accuracy and reproducibility were tested on a geometric calibrated cylinder, a dental study model, and a plaster facial model. Tests were conducted at varying distances between the object and the scanner.

It was found that, in the calibrated cylinder tests, spatial distance measurement was accurate to 0.5 mm (± 0.1 mm) in the vertical dimension and 0.3 mm (± 0.3 mm) in the horizontal dimension; in the study model test, molar width was accurate to 0.2 mm (± 0.1 mm, $P > 0.05$), and palatal vault depth could be measured to 0.7 mm (± 0.2 mm, $P > 0.05$). The facial model had an accuracy of 1.9 ± 0.8 mm. The findings suggest that the surface laser scanner has great research potential because of its accuracy and ease of use.³¹ The VI-700 has been used for the integration of 3D shapes of the dentition and face³² and also for idiopathic scoliosis.³³

In 2001, Minolta released the VI-900 as an improvement to the VI-700 series. This camera had a reported manufacturing accuracy of 0.1 mm. These cameras emit an eye-safe class I laser (US Food and Drug Administration) of wavelength 690 nm at 30 mW with an object-to-scanner distance of 600–2500 mm and a fast mode scan time of 0.3 seconds. The system uses a one-half-frame transfer charge-coupled device and could acquire 307,000 datapoints. The scanner's output data is 640×480 pixels for 3D and RGB color data.

The VI-910 and 9i are newer systems that were introduced into the market in 2004 and 2005, respectively. They work on a similar principle to the VI-700 and VI-900, but have add-on features that allow faster scanning times, higher image resolutions, and better photorealistic quality. These systems have not currently been evaluated in the literature.

Fastscan

This new-generation, lightweight, hand-held scanner, the Fastscan (Polhemus Inc, Colchester, VT, USA) emits a 670 nm wavelength laser and is manually swept across the target object in a manner similar to



Figure 2.2 Multiple camera system with structured light patterns to obtain a three-dimensional image. The image shown is the 3dMDface system (3dMD, Atlanta, GA, USA).

spray-painting. Two optical cameras are arranged symmetrically on either side of the laser generator to receive the distortions of the laser beam. An electromagnetic tracker device measures the position in space and removes the need for rigid fixation or tripods. The scanning time is normally 10–15 seconds, and the device has been used to evaluate facial swelling in patients after third molar surgery. The initial reports showed that the device had a 4% scanning error in volumetric swelling and had some patient positional problems.³⁴

Structured light techniques

The structured light technique is another broad category of systems used for capturing 3D information based on triangulation principles. Normally, a projector shines a pattern of “structured” light (which may be composed of elliptical patterns, random texture, maps, etc.) onto a targeted surface to be scanned. When the light illuminates the surface, the light pattern distorts and bends. A system of cameras at a known distance captures the reflected and distorted pattern under an angle and translates the information into 3D coordinates. An example is shown in Figure 2.2.

Single-camera systems

Tuncay and co-workers developed a series of 25 different high-density structured light patterns and evaluated the system on a mannequin made up of a skull embedded in latex. The imaging system consisted of a black and white charge-coupled device camera and a monochrome liquid crystal display projector connected to a Macintosh computer. The cameras and projectors were positioned at 30 degree angles to each other, and the mannequin was rotated on a turntable at 10 degree increments over 180 degrees. The technique produced satisfactory results, but this accuracy was reduced when a human face was utilized.^{35,36}

Enciso and co-workers in 2003 also reported on a single-camera system, consisting of a slide projector, a digital camera, and a calibration pattern.³⁷ Using a digitizer for validation purposes, landmarks were plotted and the linear distances calculated between real physical distances and image-produced distances.³⁷ The errors found ranged between 0.48 and 1.55 mm.

Two or more camera systems

Moiré fringe patterns

One of the earliest methods using the “structured” light technique utilized “moiré” fringe patterns and was first described in 1970.³⁸ Moiré topography imaging is a contour-mapping technique that involves positioning a “grating” close to an object and observing its shadow on the object through the grating. The resultant “moiré” fringes correspond to a contour line system of the object under certain conditions.

One study reported the use of a similar technique using a three-directional camera.³⁹ The cameras were placed “straight on” and at 45 degrees to the patient. The facial features were illuminated with a grating system, and the surface was captured by controlling the three shutters simultaneously. The images produced did not, however, produce photorealistic surface texture, and surface reproduction around sharp features was questionable.³ These methods have also been used in whole-body imaging, cleft studies, and facial growth imaging.^{40,41}

OGIS Range Finder RFX-IV^{42,43}

Another 3D measurement and evaluation system for facial forms was developed with a liquid crystal range finder (OGIS Range Finder RFX-IV; OGIS Research Institute Co Ltd, Osaka, Japan). This was essentially a light-based system with a resolution of approximately 0.4 mm. It is capable of measuring over 30,000 points from the entire facial surface in one second. A program was developed to identify facial landmarks using not only linear distances, but also 3D curvatures and discriminant analysis of the RGB data. The programming language was C, and the graphical interface was based on X11.3 methods of extracting data:

- extraction by anteroposterior x -, y -, and z -distances from the face;
- extraction of the 3D curvature;
- extraction by discriminant analysis of the RGB data.

Only beta versions of this system were built and reported.

CAM^{3D} systems

The CAM^{3D} (CamSorik GmbH, Braunschweig, Germany)^{44,45} is another structured light system. A sequence of phase-shifted fringe patterns of structured light are projected onto the region of interest. Data can be recorded from two charge-coupled device cameras and evaluated by means of a four-shift algorithm to receive 3D information on the shape of the object’s surface.

C3D systems

A team of orthodontists and oral maxillofacial surgeons carried out extensive research on the C3D system.^{46–53} The technique utilized two stereo-pairs of cameras positioned on each side of the patient’s

face. Under computer control, a random texture pattern was projected onto the face or a natural untextured illumination. This was used as a means to find corresponding points to line up images. The computer's task of finding corresponding points between stereo-images is called image matching and is achieved by automatic correlation. Image-matching generates a set of parallel measurements for each point with each of the stereo-pairs of images. These parallels are then converted into distances to the surfaces imaged by the stereo-pairs by a process based on triangulation known and mentioned from photogrammetric principles mentioned previously. This is known as space re-section and is a fundamental step in recovering the depth of stereo-images. The camera must be calibration before use. This is a process known as space intersection. The authors have successfully tested the 3D device on infants, in patients in surgical orthodontics, and also on study models.

3dMDface system

In the last two years, 3dMD (Atlanta, GA, USA) has launched a structured light system combining stereo-photogrammetry and the structured light technique. This system uses multiple cameras, three (one color and two infrared) on each side to capture photorealistic quality pictures. The system works by projecting a random light pattern onto a subject and capturing an image with multiple precisely synchronized digital cameras set at various angles in an optimum configuration. The capture time of the system is 1.5 milliseconds at the highest resolution, making it ideal for documentation of children. It has a manufacturer's quoted accuracy of <0.5 mm (root mean square) and clinical accuracy of 1.5% of the total observed variance.⁵⁴ Multiple studies on populations, clefts and surgery have been reported using this system.

Others

Some other newer machines include the Fiore 3D Range camera (NEC Italia, Trezzano Sul Naviglio Mailand, Italy), the 3D Hybrid Face and Object Recognition System (3Di-Matrix, Madaid, Spain), and the Rainbow 3D Camera (Genex Technologies, Inc, Kensington, MD, USA).

Video-imaging

Some other light-based systems have utilized video camera technology and recorded the number of frames captured per second. Some researchers used this to study 3D motion. One of the early studies was conducted by Caruso *et al.*, who demonstrated the feasibility of obtaining 3D trajectories of lip and jaw landmarks during chewing movements.⁵⁵

Trotman and co-workers⁵⁶ successfully validated a motion system and applied this technique to measuring facial animation, soft tissue mobility,⁵⁷ and facial expression.⁵⁸ Facial motions were captured by Motion-Analysis (Motion Analysis Corporation, Santa Rosa, CA, USA), essentially made up of three 60 Hz video cameras. Reflective markers were placed on facial landmarks, and the subjects were asked to perform a number of preassigned facial movements. 3D maximum motion amplitudes were calculated and were significantly more, some up to 43% more, than the two-dimensional data.⁵⁹ Student's *t*-test and Pearson product movement correlation coefficients were used to test for significant differences between repetitions. The results show moderate-to-excellent reliability of the range of motion for the landmarks over all animations according to the authors. This system was also utilized for vector and interlandmark variations,^{58,60} and sex and facial shape comparisons.⁶¹ Some recent innovations have added on sound and virtual animation.⁶²

In a further modification of the video based technique, Eian and Poppele⁶³ were able to use just a single video camera system to capture 3D motion using complex algorithms.

Radiographic techniques

Conventional computed tomography

Medical CT started as early as 1967 and many generations of these machines have been created. The method of classification for each system is based on the organization of the individual parts of the device and the physical motion of the beam in capturing the data.

First-generation scanners consisted of a single radiation source and a single detector, so information was obtained slice by slice. The second generation was introduced as an improvement, and multiple detectors were incorporated within the plane of the scan. However, these detectors were not necessarily continuous, nor did they span the diameter of the object.

The third generation was made possible by an advancement in detector and data acquisition technology. These large detectors reduced the need for the beam to translate around the object to be measured and were often known as the “fan-beam” CTs. Ring artifacts were often seen on the images captured, distorting the 3D image and obscuring certain anatomic landmarks. The fourth generation was developed to counter this problem. A moving radiation source and a fixed detector ring were introduced. This meant that modifications to the angle of the radiation source had to be taken into account, and more scattered radiation was seen.

Finally, the fifth (sometimes known as the sixth) generation of scanners was introduced to reduce “motion” or “scatter” artifacts. As with the previous two generations, the detector is stationary and an electron beam is electronically swept along a semi-circular tungsten strip anode. The radiation is produced at the point where the electron beam hits the anode, and results in a source of X-rays that rotates around the patient with no translation components or moving parts. Projections of the X-rays are so rapid that even the heart beat may be captured. This has led some clinicians to hail it as a four-dimensional motion capture device.

There are a number of limitations to these systems. They require a dedicated facility and are very expensive. The images captured on the detector screens are made up of multiple slices that are “stacked” to obtain a final complete image, making the process time-consuming and less cost-efficient. Furthermore, the radiation exposure to the patient has limited its usage to complex craniofacial problems and specialized diagnostic information only.

Cone beam computed tomography

Craniofacial cone beam CT (CBCT) was designed to deal with the problems of the conventional CT scanning devices. The radiation source consists of a conventional low-radiation X-ray tube, and the resultant beam is projected onto a panel detector. The cone beam produces a more focused beam and much less radiation scatter compared with the conventional fan-shaped CT devices.⁶⁴ This significantly increases the X-ray utilization and reduces the X-ray tube capacity required for volumetric scanning.⁶⁵ It has been reported that the total radiation is approximately 20% of conventional CTs and equivalent to a full mouth periapical radiographic exposure.⁶⁶

These component innovations are significant and allow the CBCT to be less expensive and smaller. Furthermore, the exposure chamber (known as the “head”), is custom built and hence reduces the amount of radiation exposure. The images are comparable to those of conventional CT and may be displayed as a full head view, a skull view, or regional components. There are currently four main system providers in the world market. As clinical research in this technology escalates and as the costs reduce, there is no doubt that more providers will begin to invest in and promote this technology.

The machines currently available produce high-quality 3D skeletal and soft tissue information. However, there are differences in size, area of image capture, and clinical usage.⁴

Radiation issues

Despite the CBCT device's capability in producing excellent high-quality 3D skeletal and soft tissue images, clinicians must be cautious about managing the risk and benefits to the patient as part of the process of obtaining the images.

Soft tissues and photographic color contrast

The CBCT is excellent for imaging hard tissue structures and some soft tissue components. However, it does not have the ability to map out exactly the muscle structures and their attachments. These intricate structures have to be imaged using conventional magnetic resonance imaging (MRI) technology that, incidentally, does not predispose the patient to radiation exposure.

Patient position is another noteworthy point as it will ultimately affect the image quality of the soft tissue structures due to the "pull" of gravity on the soft tissues and the different resting positions of the jaw when the patient is supine vs. sitting upright. A clinically reproducible position will lead to a more accurate picture of the jaw and soft tissues at the time of image capture.⁶⁷

Finally, CBCT external soft tissue images do not capture the true color and texture of the skin. Therefore, in order to obtain photograph-quality resolution, manipulation of the images is still required. Successful attempts to map tissue texture maps onto conventional CTs have been reported and may be similarly applied to this new technology.⁶⁸ An example is shown in Figure 2.3. Therefore, 3D devices like stereo-photogrammetry and laser scanning are still the mainstay of soft tissue texture capture. Some centers have started testing the radiologic doses of the machines, but the testing methods have been a subject of debate.⁴



Figure 2.3 Image of a surface acquisition scan projected onto a cone beam computed tomography surface. (Courtesy of University of Texas Health Science Center, Houston, TX, USA.)

Others

Magnetic resonance imaging

MRI scans have traditionally been used as a technique for two-dimensional imaging of body structures. Most systems are made up of a large cylindrically shaped electromagnet, equipped with coils along with transmitters and receivers of radiowaves. A study subject is placed within the system, and a powerful magnetic field and radiofrequency pulses are generated. This causes a polarization of the hydrogen atoms contained in the tissues, and the subsequent depolarization emits radiation (similar to radiowaves). The subsequent data collected are generated into 3D images for analysis.

MRI has proven useful in a variety of head and neck applications and is a relatively safe but costly procedure.⁵ It has been applied to the analysis of temporomandibular joints,⁶⁹ the preoperative planning of tumor resection,⁷⁰ and maxillary sinus evaluation.⁷¹ These images have also been combined with CT scans for planning surgical treatment.⁷²

Three-dimensional ultrasound (ultrasound holography)

This technique has been used mainly in fetal visualization and obstetrics, but applications have also been developed for the head and neck. A high-frequency wave, normally between 3.5 and 7.0MHz (although frequencies above and below this range are also used), is emitted from a special probe placed in contact with the area of interest. Repeated ultrasound beams are able to scan thin slices of an area and reflect back to the same transducer. The production of a 3D hologram is not time-consuming and has been used by maxillofacial surgeons for visualization of the soft tissues and organs. These include the tongue, nose, and salivary glands.⁷³

Pulsed holography

Holographic technology has been applied successfully in a number of reported research publications.⁷⁴ In general, holograms are recorded with a single laser pulse of 25 nanoseconds' duration and stored in a photosensitive material. After an automatic wet chemical processing, the hologram can be optically reconstructed and digitized. This process is termed hologram tomography. This technique has been successfully applied in facial anthropometry and the acquisition of facial surface models.

CHALLENGES AND PITFALLS

Every available system provides a representation of the object imaged. Due to inherent faults in technology and the distortion of light, none of the 3D imaging systems is accurate over the full field of view. Furthermore, all systems suffer from the potential for patient movement and alterations of facial expression between the multiple views needed to construct a 3D model of the face.⁷⁵⁻⁷⁷ However, the challenges to re-create the virtual environment for better clinical care and the assessment of outcomes cannot be ignored. The continuous improvements in technology and software mean that researchers and clinicians are closer to realistic 3D imaging, although it may never be fully attainable. Table 2.2 outlines the advantages and disadvantages of the various systems.

Table 2.2 Advantages and disadvantages of the different three-dimensional imaging systems

Device	Advantages	Disadvantages
Photogrammetry	Cheap and easy to set up	Magnification errors Tedious work to map surfaces Pseudo three-dimensional image
Lasers	High resolution Quick capture Noninvasive Contour topology and surfaces Medium photorealistic quality	Expensive equipment Technique-sensitive
Computer-aided structured light	Very rapid capture Photorealistic Noninvasive	Technique sensitive Varying resolution quality
Video-imaging	Multiple motion capture Photorealistic Speech and animation capture	Low resolution Processing capabilities required
Radiation	Reasonable resolution Good correlation to hard tissues	Radiation dosage not feasible for multiple exposures Expensive equipment Long scan time

CLINICAL APPLICATIONS

A number of clinical applications have since been developed for surface imaging devices but only three will be discussed in this chapter:

1. gender analysis
2. craniofacial anomalies
3. surgery.

Gender analysis

One interesting application of the average facial template is to compare the morphologic differences in facial features specific to gender groups. Using an in-built “iterative closest point” algorithm within commercially available software, the male and female faces were overlaid over one another.^{78,79} It was shown that facial differences did exist between males and females. These differences were predominately in the cheeks, brows, and lower face (Figure 2.4).

Craniofacial anomalies

The average faces that are described represent the true variation in facial morphology in a cohort of children. This method does not rely on mathematical manipulation to construct an average surface mesh⁸⁰

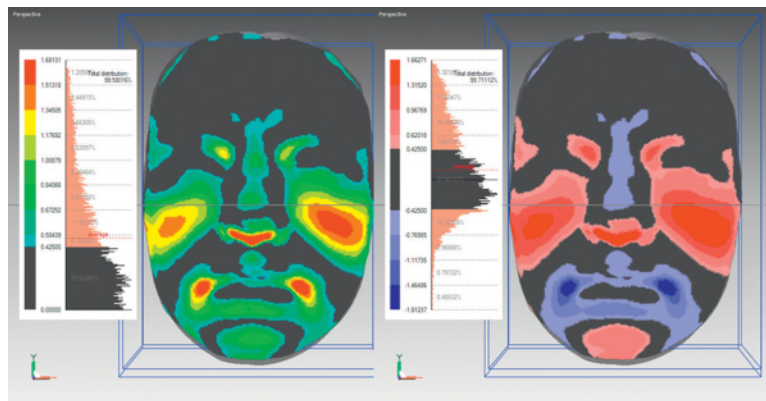


Figure 2.4 Color maps indicating the differences between males and females at age 12 years.

and is age- and gender-specific. The average facial meshes may be used as a template to determine morphologic differences between normal subjects and those with craniofacial anomalies. An example previously illustrated is described.⁸¹

The superimposition of a patient with a cleft lip and palate anomaly onto the gender- and age-specific 11-year-old template showed up the 3D severity of the defect (Figure 2.5). This defect corresponded well with the location of the anomaly (i.e., the right side). One interesting observation noted is the asymmetric shape defect and the potential complications that clinicians would need to address during treatment. For example, any form of treatment to advance the maxilla would require an asymmetric rotational component to compensate for the greater defect on the right side. In addition, all treatment would need to produce a soft tissue movement equivalent to 8 mm in an anterior direction. The volume of the defect was recorded as $3.79 \times 10^6 \text{ mm}^3$.

Image-guided surgery

Surface imaging has also been combined in part with traditional CT imaging to create a novel and image-guided surgery. Marmulla and co-workers^{82,83} described the use of a high-resolution laser surface scanning device (Minolta VI-910) for patient registration in cranial computer-assisted surgery. Surface registration was performed by the navigational system Surgical Segment Navigation (SSN++, developed by Carl Zeiss, University of Heidelberg, Germany), which uses infrared transmission technology enlarged by the laser scanner. This allows the laser coordinate system to calibrate with the infrared system to navigate infrared-transmitting instruments. This technique has been successfully applied in the study of 22 patients.

CONCLUSION

Many 3D imaging devices are currently available for soft tissue imaging. New techniques and sophisticated software tools now allow clinicians to manipulate the images and make them relevant to the clinical setting. These imaging tools have the advantages of being quick, easy to use, and noninvasive, unlike

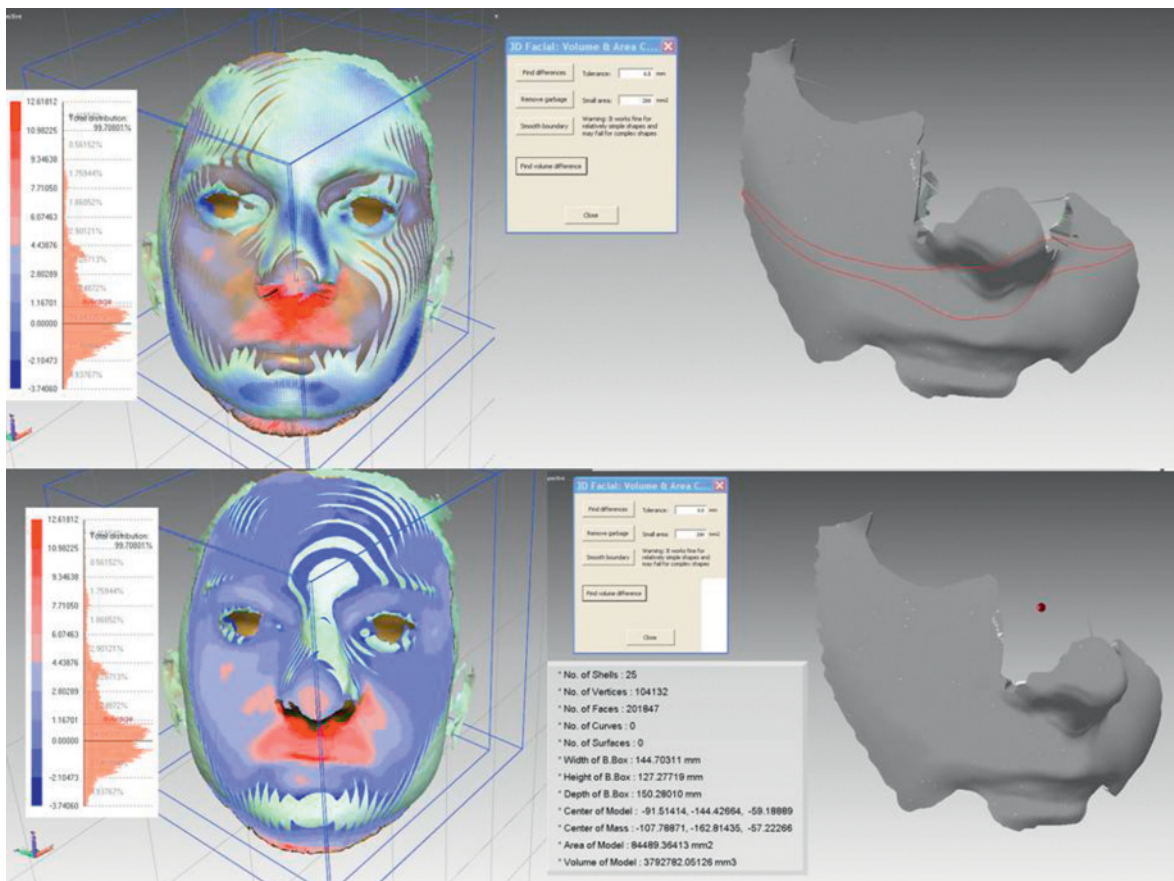


Figure 2.5 Surface differences as seen on a patient with a cleft lip and palate versus corresponding age-/gender-specific facial averages. The size, shape, and volume of the defect can be isolated.

other 3D hard tissue imaging systems that present radiation issues. As the techniques become readily available, surgical and treatment simulations will also be enhanced, allowing clinicians to better plan and predict treatment outcomes.

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3 Diagnostic Imaging

Nicholas Drage and John Rout

INTRODUCTION

X-rays were discovered by Wilhelm Röntgen in November 1895.¹ He was working with a Crookes tube and noticed that when the tube was activated, barium platinocyanide plates lying close by fluoresced. Since he could not see what was being emitted from the tube, he named them X-rays (X meaning “unknown”). Within a few weeks, radiographs of the teeth were being taken independently in Germany, the United States, and England. At this time, dental exposures lasted several minutes and used glass photographic plates wrapped in black paper.

Since then, there have been major developments in equipment design to improve both safety and image quality. Current United Kingdom recommendations for intraoral equipment include the use of high-kilovoltage constant potential machines with long focus-to-skin distances and rectangular collimation.² Film holders and beam-aiming devices are also essential for periapical and bitewing radiography.

Panoramic radiography using a rotating extraoral source of radiation was first patented by A.F. Zulauf in 1922.³ In 1933, a machine using a narrow collimated beam was designed,⁴ but it is generally accepted that the first rotating panoramic machine was produced by Paatero in Finland.⁵ The early devices used a single centre of rotation,⁶ but today’s modern machines use a continuously moving centre of rotation. This produces a horseshoe-shaped focal layer that corresponds to the shape of the “average” jaws. Accurate patient positioning is important to reduce distortion in the image.

The lateral cephalometric view of the facial bones using a long focus-to-film distance was introduced by Broadbent in 1931,⁷ and this technique continues to be utilized today. It is important to note that even when the patient is positioned correctly, there will never be perfect superimposition of the right and left sides of the facial skeleton, because the X-ray beam is divergent.

Broadbent also described the posteroanterior radiograph taken in a cephalostat. Using an acetate overlay over the paired cephalometric lateral and posteroanterior views, landmarks on one view can be

visualized along the corresponding plane on the other view, enabling simple “three-dimensional” (3D) imaging. Modern 3D cephalometry uses a similar technique, but the acetate overlay has been replaced by computerized algorithms. The technique has been used successfully^{8,9} and carries a low radiation dose; however, it is susceptible to errors,¹⁰ and no soft tissue assessment can be made. Other imaging modalities have now superseded cephalometric radiography for 3D analysis.

There have been significant developments in image receptors. The first commercially available dental film was produced in 1913 by the Eastman Kodak company. Today’s modern film is much faster and requires a shorter exposure to produce a diagnostically acceptable image. Currently, F speed is the fastest film available. Extraoral radiography uses cassettes containing intensifying screens. The screens emit green or blue light when irradiated to expose the light-sensitive film sandwiched between them. The screens should be of the “rare earth” type to reduce the dose as well as improving image quality.

Francis Mouyen, a dental student in France, developed the first digital systems for taking radiographs of the teeth, and these became available in Europe in the mid 1980s.¹¹ Digital systems are classed as either direct or indirect. Direct systems use technology based on either a charge-coupled device or a complementary metal oxide semi-conductor, whereas indirect systems use a photostimulable phosphor plate. Digital systems offer many advantages over conventional radiography, including dose reduction, elimination of processing errors, and the ability to enhance the images in order to visualize disease more easily. The data can be imported into other software programs for automatic image analysis such as anatomic landmark identification.¹²

Radiographs form an essential part of orthodontic diagnosis and treatment planning. One of the main shortfalls of conventional radiography is that the images are two-dimensional (2D). 3D imaging is becoming increasingly popular in diagnosis, in treatment planning, and in the prediction of treatment, particularly for orthodontics and orthognathic surgery. The techniques employed are computed tomography (CT), cone beam CT (CBCT) and to a lesser extent magnetic resonance imaging (MRI).

COMPUTED TOMOGRAPHY

CT was invented by Sir Godfrey Hounsfield while working for Electric and Musical Industries Limited (EMI). Clinical input was provided by Dr James Ambrose, a neuroradiologist, and the first head scan was performed on a prototype unit in 1971. Hounsfield’s name is given to the unit of attenuation that is used today. The early machines acquired and reconstructed the images very slowly. However, CT scanners have developed over the years so that CT imaging is very quick and is considered by many to be the “gold standard” in the imaging of craniofacial anomalies.

A CT scanner comprises a table and a gantry (Figure 3.1). The gantry houses both the X-ray source, which produces a narrow, fan-shaped beam, and the detectors, which are either gas-filled ionization chambers or solid-state scintillation detectors. To acquire the scan, the supine patient is moved through the gantry aperture while the X-ray beam rotates around the patient. The beam is attenuated as it passes through the patient, and this generates an electrical signal in the X-ray detector that is proportional to the number of X-rays hitting the detector. In sequential scanning, once the X-ray source has completed a single rotation, the patient is moved through the aperture a short distance and another rotation is carried out.

Third-generation type CT scanners use a small array of detectors that are located directly opposite the X-ray source. The detectors rotate so that they are continuously exposed to the X-ray beam. In fourth-generation scanners, there is a complete ring of stationary detectors, and only the X-ray source rotates (Figure 3.2). With the advent of slip-ring technology, it has become possible to supply the necessary

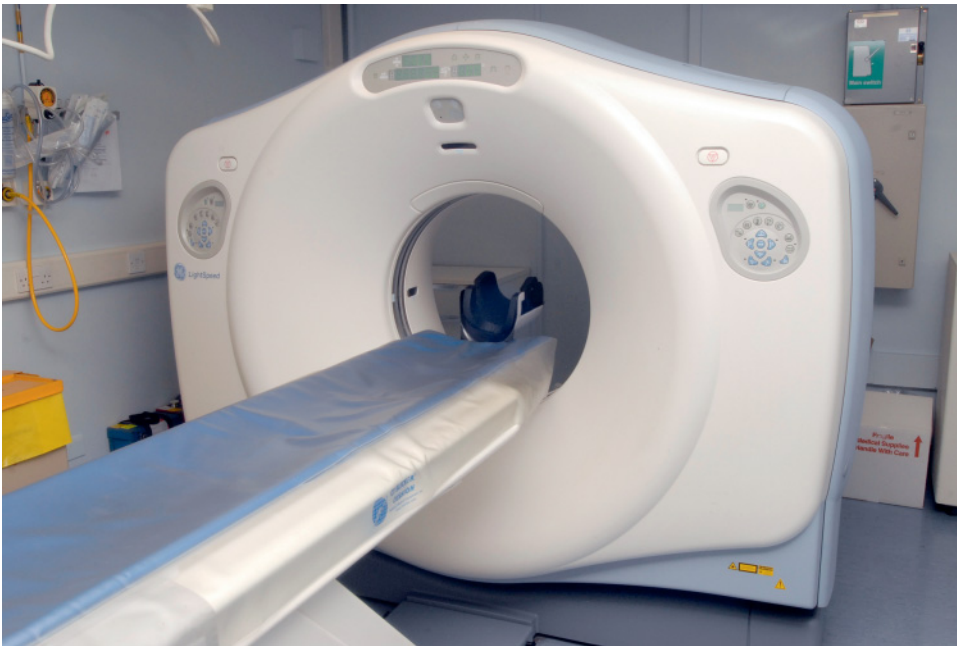


Figure 3.1 An example of a modern computed tomography scanner, showing the table, head support, and gantry. (With permission from Cardiff University, UK.)

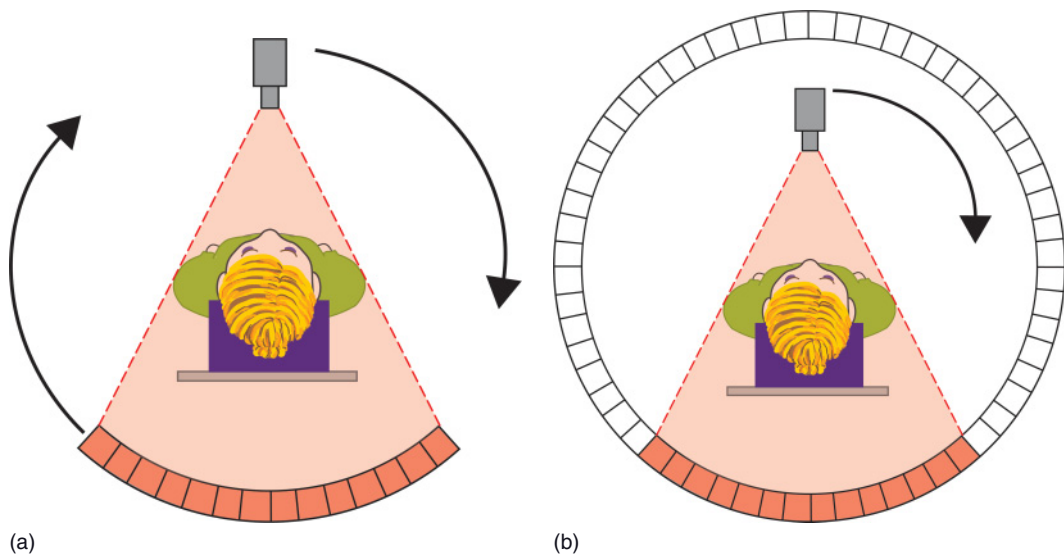


Figure 3.2 Diagrammatic representation of third- and fourth-generation computed tomography scanners. (a) In third-generation scanners, both the X-ray source and detectors rotate around the patient. (b) In fourth-generation scanners, there is a complete ring of detectors and only the X-ray source rotates. (With permission from Cardiff University, UK.)

power to the X-ray source continuously as it rotates. This allows the patient to be moved continuously through the aperture as the X-ray beam rotates, producing a helical dataset. This is known as spiral or volume scanning. It has several advantages over sequential scanning, including shorter acquisition times, reduced movement artifact, reduced partial volume artifact, and better reconstruction into coronal, sagittal, and oblique planes.

Multislice CT (MSCT) is a procedure in which 4–16 slices are acquired simultaneously. This has several advantages over conventional CT in that it is fast and offers increased flexibility, including easier 3D reconstructions.¹³ This high-dose technique should only be considered if there is a significant increase in the expected diagnostic yield.

Low-dose techniques in which either the milliampère to the X-ray tube is reduced or the pitch of the spiral is increased are being developed. The results of these studies are promising, and significant dose reductions can be obtained without any appreciable loss in diagnostic information. This technique has the added advantage over CBCT in that the soft tissues can still be evaluated.^{14,15}

Image reconstruction

The dataset comprises a series of projections that are reconstructed using mathematical algorithms such as the Feldkamp algorithm – a type of filtered back projection.¹⁶ With sequential imaging, each slice of data is made up of a matrix of voxels (volume elements). There are typically 512×512 voxels in a slice, with the width of each voxel being equivalent to the slice thickness. A voxel in a 2 mm slice would typically be $0.5 \text{ mm} \times 0.5 \text{ mm} \times 2 \text{ mm}$. The reconstructed image is composed of a matrix of pixels (picture elements). Each individual pixel is assigned a Hounsfield number dependent upon the linear attenuation coefficient at that particular pixel relative to water. This process is shown in Figure 3.3. Typical Hounsfield numbers are shown in Table 3.1.

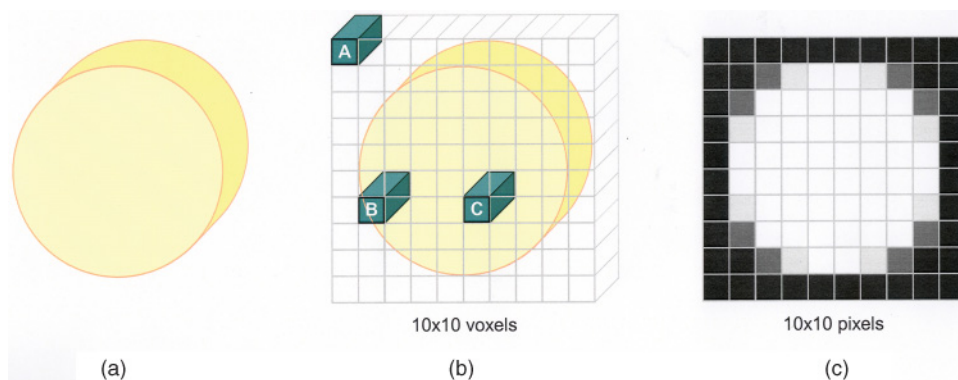


Figure 3.3 Diagram showing the construction of the image in conventional computed tomography. In this example, a single high-density circular disc is scanned, and the voxel and pixel matrices used are both 10×10 ; the original object is shown on the left (a); the voxel matrix in the middle (b), and the pixel matrix on the right (c). Since at voxel A there will be no attenuation of the beam, it will be displayed black in the final image. At voxel C, the beam is fully attenuated and so is displayed white. At voxel B, the beam is partially attenuated and is displayed mid-gray. In the example, the circle appears very “boxy,” but in reality the matrices are much larger (typically 512×512) and would appear round in the final display. (With permission from Cardiff University, UK.)

Table 3.1 Table showing the Hounsfield numbers for some of the tissues

Tissue	Hounsfield number	Display
Bone	+1000	White ↓ Black
Muscle	+35	
Water	0	
Fat	-100	
Air	-1000	

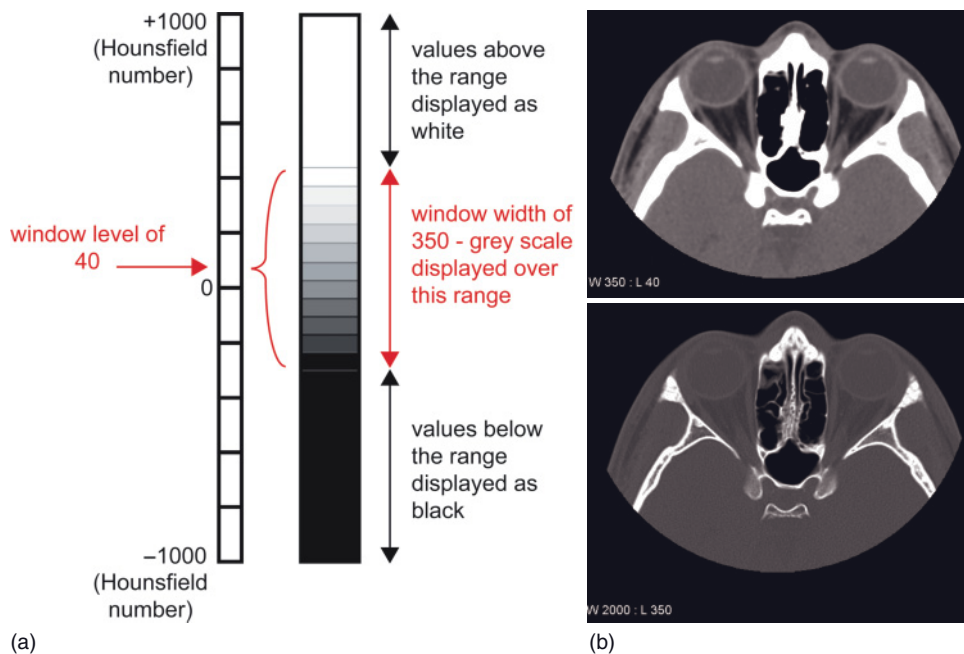


Figure 3.4 In the diagram, typical values for demonstrating soft tissue have been chosen (window level 40, window width 350) (a). Examples are shown of axial images through the orbits displayed on soft tissue windows (window level 40, window width 350) (b, top), and bony windows (window level 350, window width 2000) (b, bottom). Using soft tissue windows, fat, muscles, and the globe are easily distinguished, but the bone is uniformly white with no detail. Using bony windows, the detail within the bone is seen. (With permission from Cardiff University, UK.)

The Hounsfield number given in Table 3.1 for bone is for average bone; for dense compact bone such as the petrous temporal bone, even higher Hounsfield numbers would be assigned.

Before the picture is displayed, it is necessary to “window” the image. This allows the tissues of interest to be displayed over a suitable gray scale. The window level corresponds to the average Hounsfield number of the particular tissue under investigation, and the width is the range of Hounsfield numbers over which the gray scale is displayed. Tissues outside the range are displayed as either white (if the number is higher than the width) or black (if the number is lower than the width). This is shown in Figure 3.4.

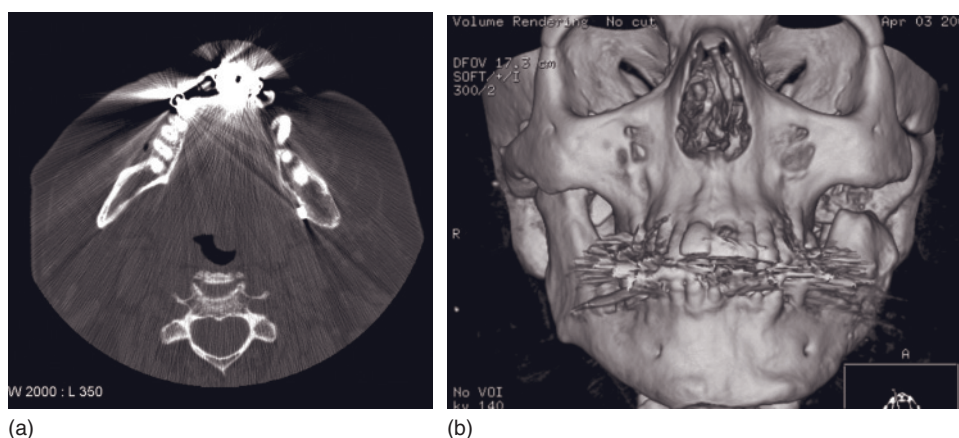


Figure 3.5 An axial slice and a three-dimensional reconstruction of the same patient showing marked amalgam artifact. (Courtesy of Mr Michael Fardy.)

Amalgam can significantly degrade the images, causing “star artifacts” that can greatly decrease the diagnostic yield. This affects both the axial images and also any 3D reconstructions that are planned (Figure 3.5).

3D reconstruction

Several types of 3D reconstruction are possible, including maximum-intensity projection, surface rendering, and 3D volume rendering. These are reviewed in an excellent article by Calhoun *et al.*,¹⁷ and it is beyond the scope of this chapter to describe the algorithms utilized to produce the reconstructions. Briefly, however, with a maximum-intensity projection only the voxel with the highest Hounsfield number along the path of the X-ray photon contributes to the density displayed at each pixel. Although the resultant image may appear 3D, this is misleading as no true 3D relationships are displayed. Its main application is in angiography (Figure 3.6).

Surface rendering reconstructs surfaces as if a light is being shone onto the object to produce bright and shadowy areas. The surfaces are chosen by thresholding the data so that only the required surface type is displayed. 3D volume rendering utilizes all the voxels along the ray to ultimately produce the image. High computing power is necessary to perform the appropriate calculations, but it is possible to change the opacity of 3D objects so that underlying structures can be seen. 3D volume rendering is becoming the most useful of these techniques, and the reconstructions can be produced using data generated from CBCT imaging.

Accuracy

The smaller the voxel size, the better the resolution, but as ever there is a trade-off between image quality and radiation dose. Early studies assessing the accuracy of measurements taken from 3D images showed that the methods had to be improved before accurate measurements could be made.¹⁸ However, recent studies are much more promising.

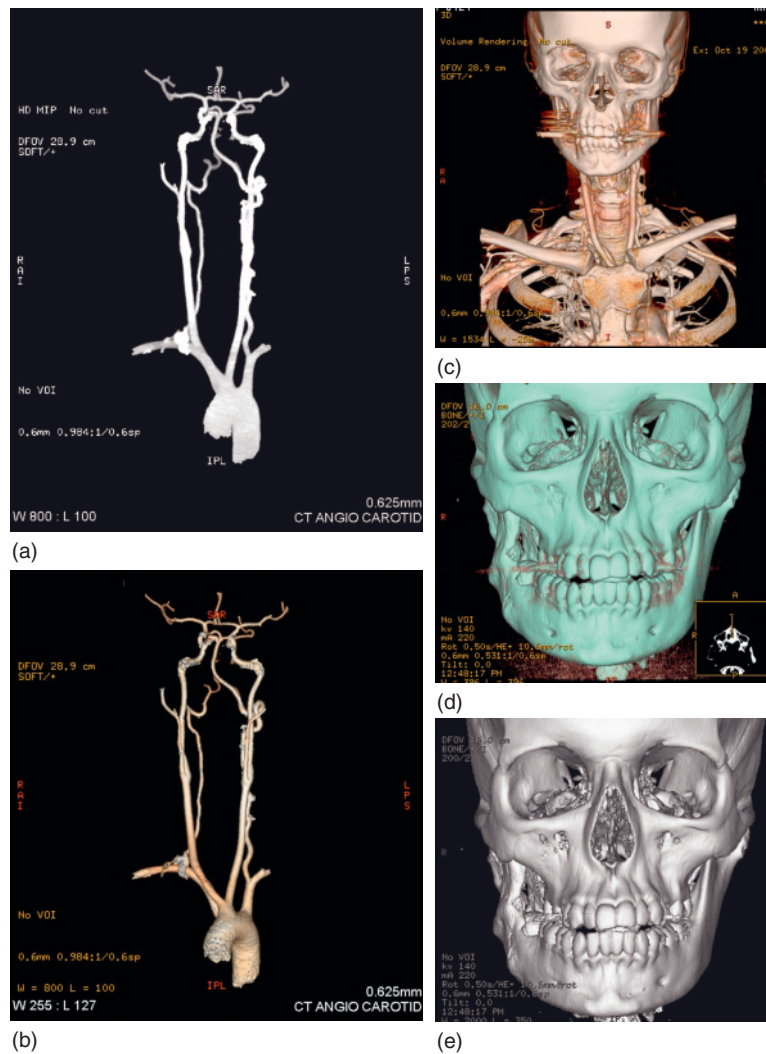


Figure 3.6 (a) Maximum-intensity projection of a carotid arteriogram and (b) volume-rendered reconstruction of the same arteriogram. (c) Volume-rendered image showing both the vascular and bony anatomy of the head and neck region. (d) Volume-rendered three-dimensional reconstruction and (e) surface-rendered reconstruction of the same patient. Although the images appear similar, the advantage of volume-rendering is that the translucency of the reconstruction can be altered to see below the bone surface. (Courtesy of Dr Maggie Hourihan.)

In one study, the relative position of the inferior dental canal to the alveolar crest was investigated, and no statistically significant differences were found between 2D CT, 3D CT, and direct measurements.¹⁹ However, 2D CT consistently overestimated the distances, and 3D CT underestimated them. In another study, both the precision (reproducibility between two different observers) and the accuracy (validity) of 3D volume-rendered images produced from MSCT data were investigated, this time for linear measurements in the region of the mental foramen. It was found that the linear measurements were both valid and demonstrated a high degree of precision.²⁰

In another cadaver study,²¹ 13 heads were imaged using spiral CT. Linear measurements used in anthropometric analysis were identified in both 2D and 3D. In addition, soft tissue thickness was also measured. The error between the mean actual and the mean 3D linear measurements was 0.83% for bone and 1.78% for soft tissue, with low standard deviations, demonstrating high accuracy for both bone and soft tissue. Overall, these 3D applications are suitable for orthognathic planning.

Quantitative CT has been used extensively in the measurement of bone mineral density (BMD) in the diagnosis of osteoporosis. The advantage of quantitative CT is that the true volumetric density can be measured of either the trabecular or cortical bone at any site, including the jaws.²² CT is considered to be one of the most accurate methods of assessing BMD in the jaws.

Radiation dose

When considering the radiation dose of an investigation, the effective dose is usually cited because it allows comparisons between different radiographic examinations. It takes into account both the type of radiation employed and the radiosensitivity of the tissues irradiated. The effective dose from CT of the mandible ranges from 364 to 1202 μSv , and that of the maxilla from 100 to 3324 μSv .²³ The marked variation is likely to be due to different scanning parameters employed. When “low-dose” techniques, as described earlier, are used there may be an eightfold decrease in skin dose.²⁴

Clinical applications

CT is extensively used in the evaluation of tumors in the head and neck region. Both primary and metastatic spread may be assessed, with CT and MRI often being complementary in these cases. Iodinated contrast is often used to help delineate normal anatomy from disease and to investigate vascular anomalies.

Because CT is well suited to visualizing bone morphology in 3D, it has been used extensively to assess facial asymmetry.²⁵ Although there can be difficulty in finding landmarks that are not affected by deformity, the external auditory meatus may be considered as a suitable reference landmark.²⁶ With regard to a stable reference plane, the Frankfort horizontal plane has been suggested.²⁷ 3D volumetric data may be used to produce 3D cephalographs. The traditional landmarks used on 2D cephalometry may also be placed in 3D to allow a true global assessment of the patient.²⁸ It is interesting that the landmarks on the 2D cephalograph are often imprecise and may not reflect the actual position of these structures on the 3D reconstructions (Figure 3.7).

In patients with clefts of the maxillary alveolus, it is important that sufficient bone is grafted into the cleft to allow spontaneous eruption of the canine into the dental arch. CT has been used to preoperatively assess the volume of grafted bone required.^{29,30} 3D CT will also show the spatial relationship of the unerupted teeth so an assessment of likely spontaneous eruption can be made. Overall, CT seems to give a better assessment of outcome than conventional radiography,³¹ but it should only be used in selected cases. CT has also been used to evaluate secondary bone grafting.^{30,32} Resorption of the graft seems more likely if teeth are absent or if orthodontic intervention is necessary to align the teeth.³⁰

3D CT reconstructions have been used to assess craniofacial disorders such as Apert and Treacher Collins syndromes. It aids confirmation of the diagnosis and helps in detailing the sutures and synostoses.³³ Examples of these conditions are shown in Figure 3.8. Movement artifacts can be problematic as the patients are often very young when they are scanned, but this may be reduced using MSCT. Since

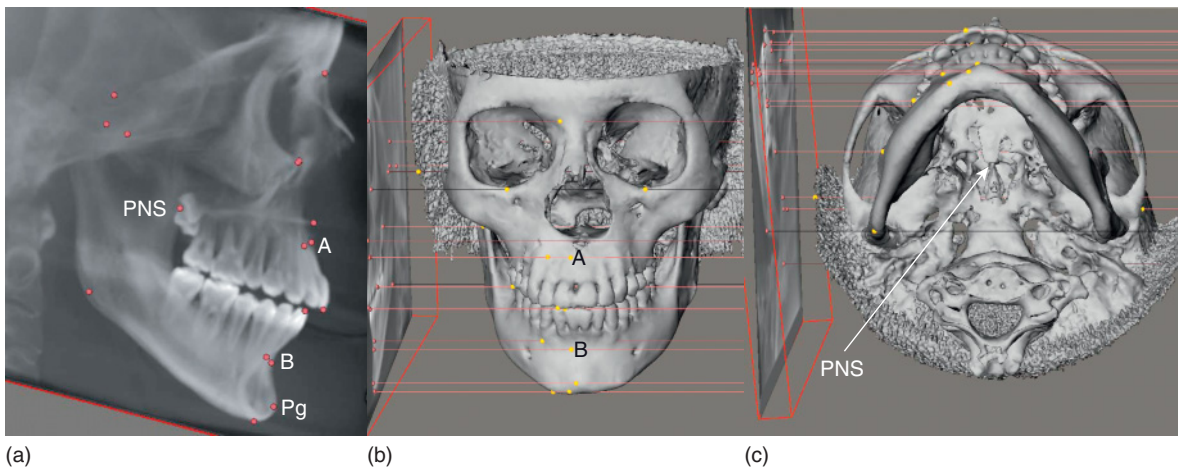


Figure 3.7 The points are placed on the lateral cephalogram (far left), and these points are projected onto the three-dimensional model. The points on the three-dimensional model do not coincide with the midline points A and B and pogonion (Pg). The postnasal spine (PNS) marked on the radiograph is 8 mm in front of the real PNS. In this example, a cone beam computed tomography scan has been used to generate the three-dimensional model (Maxilim®, Medicim NV, Belgium).

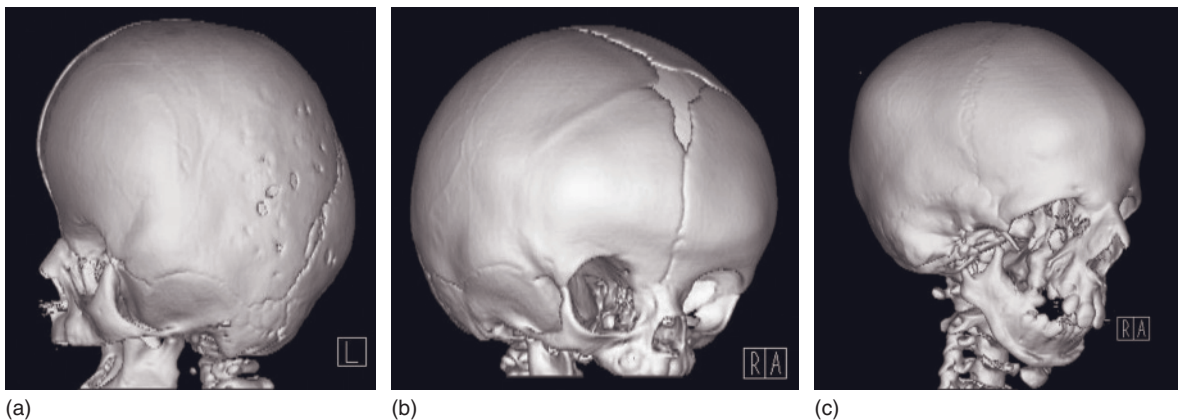


Figure 3.8 Three-dimensional reconstructions of craniofacial disorders. (a) Apert syndrome, showing an elongated or tower-shaped skull due to craniostenosis. (b) Craniosynostosis, following premature closure (synostosis) of the right coronal suture. (c) Treacher Collins syndrome with absence of the zygoma. (With permission from Dr Helen Williams, Birmingham Children's Hospital, UK.)

only a limited amount of the cranium can be scanned using CBCT, it is unlikely that this modality will help, particularly if the abnormality involves the posterior cranium.

CT has also been recommended prior to bilateral sagittal split osteotomies to help identify the mandibular canal, as it is superior to conventional spiral tomography in locating this structure. However, CT is not necessary for all patients, although it may prove useful in those with a thin ramus or with marked facial asymmetry.³⁴

Several software programs have been developed that allow the planning of osteotomies in 3D. These allow trial bone cuts and bone movements to be made and alert the operator if the proposed movements of the jaws are not possible or are likely to cause collision between adjacent anatomic structures.³⁵ These programs can also be used to predict the final bony and soft tissue profiles, which may prove extremely useful in planning complicated orthognathic surgery.³⁶ Similar programs may also be used when planning distraction osteogenesis. The 3D data are imported into the software, and the proposed cuts in the bone are made “virtually” on the 3D model. The fragments are then moved into the proposed position. From this, a vector is calculated so that a suitable design of distraction device is used and is correctly positioned.³⁵ Vectors may also be calculated on a rapid prototyping model,³⁷ and both techniques appear to be comparable.³⁸

In addition, 3D data from CT scans can be used to produce a virtual set-up of the teeth within the dental arch. This process merges the CT data with data from the laser-scanned study models. This allows the operator to assess the relationship of the teeth to the bone before treatment and also assess the degree of fenestration of bone that may be present following planned tooth movements.³⁹ Similar multimodal fusion techniques have also been used for planning orthognathic surgery. The technique of merging CT data with the laser-scanned study models allows the post-surgical relationships of the teeth and jaws to be realized virtually and allows quantification of the desired surgical movements to produce the optimum result (Figure 3.9).⁴⁰

Double-CT techniques combining CT scans of the jaws and CT scans of the study models have also been suggested to produce the virtual model of the teeth and jaws.⁴¹ However, at present, laser scanning has been shown to be superior to CT in its accuracy of depicting the study casts.⁴² It is also possible to use volume-rendered MRI scans in some orthognathic planning software programs.

CT has been extensively used to examine the bony aspect of the temporomandibular joint (TMJ). It is used to evaluate trauma (Figure 3.10) and bony neoplasms, and has been shown to be accurate in assessing the condyle and mandibular fossa in patients with rheumatoid arthritis.⁴³

CT is the imaging modality of choice for imaging complex or severe maxillofacial trauma (Figure 3.11). Often surgical landmarks are difficult to identify on axial slices, and 3D reconstructions help with their accurate identification.^{44,45} It has also been used in the assessment of the volume of bone necessary to graft traumatic defects.⁴⁶ In addition, rapid prototype models may also be constructed to aid diagnosis and treatment planning (Figure 3.12).

CONE BEAM COMPUTED TOMOGRAPHY

CBCT, or digital volume tomography, is an exciting new development in the field of maxillofacial radiology. However, its use in medical imaging is not new as these systems were already being used in vascular imaging and radiotherapy planning. The first commercially available CBCT scanner, the NewTom-9000 (Quantitative Radiology, Verona, Italy) was produced in 1996. Since then, many of the major manufacturers of dental imaging equipment have produced or are developing CBCT units specifically for imaging the teeth and the maxillofacial skeleton.

The machines are significantly cheaper than conventional CT machines, principally because the X-ray tube used has a much lower heat capacity and the technology used is less complex.⁴⁷ The detectors comprise either an image intensifier linked to a charge-coupled device, or an amorphous silicon flat-panel detector consisting of a caesium iodide scintillation screen and photosensor array.⁴⁸ The machines are generally smaller than conventional CT machines. Superficially, some may look very similar to

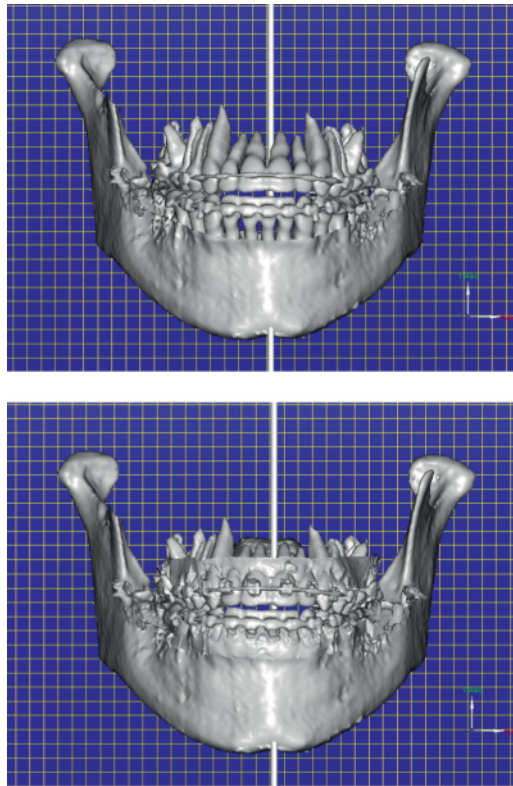


Figure 3.9 Three-dimensional segmentation of the mandible and maxillary teeth (top). The scan data are fused to data obtained from three-dimensional laser scanning of the mandibular and maxillary study casts in order to plan orthognathic surgery (bottom).

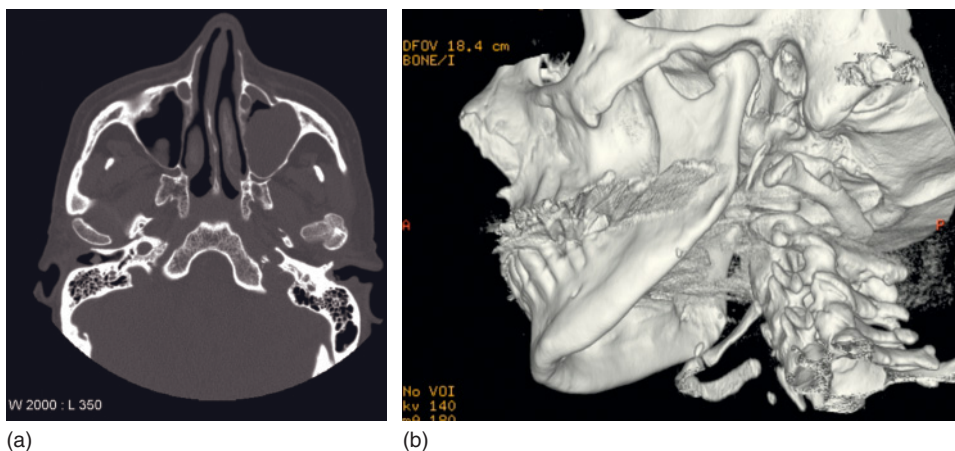


Figure 3.10 Axial slice (a) and three-dimensional reconstruction (b) through the left temporomandibular joint showing an abnormally shaped condyle that had previously been fractured. The condylar head had been displaced medially following the original traumatic episode. (Courtesy of Mr Michael Fardy.)

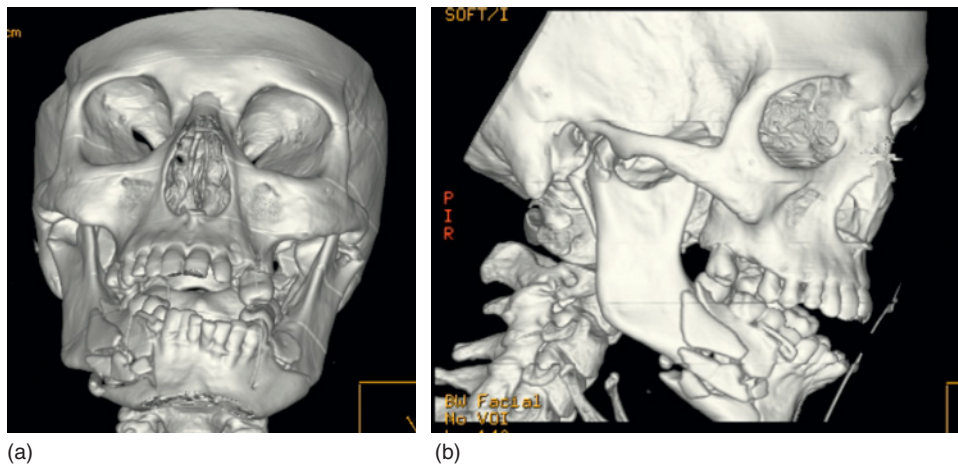


Figure 3.11 Three-dimensional computed tomography reconstruction showing multiple fractures of the mandible including a comminuted fracture of the right body. (Courtesy of Mr Andrew Cronin.)

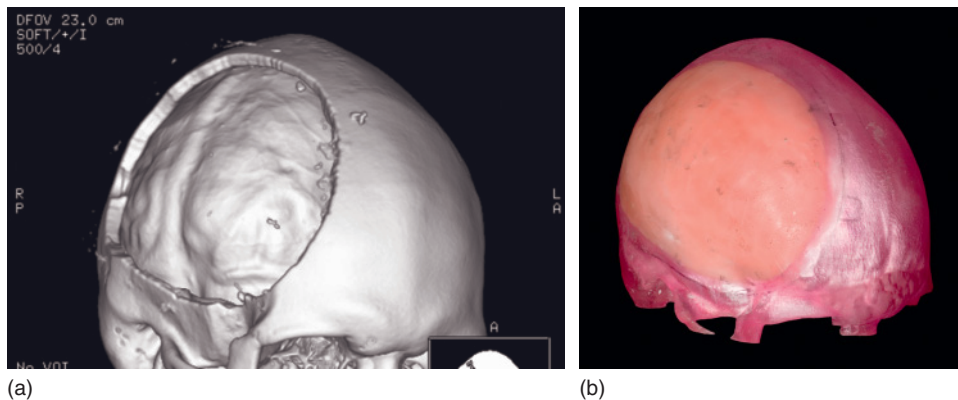


Figure 3.12 Three-dimensional reconstruction of the skull. This shows a defect in the skull following a decompression craniectomy (a). The data from this have been used to construct a rapid prototype model. The defect has been filled in with wax, and from this a titanium plate can be constructed to repair the surgical defect (b). (Courtesy of Mr Andrew Cronin.)

conventional CT scanners, but no moving gantry is employed and the table does not move through the aperture. However, most machines resemble panoramic machines, with the patient either sitting or standing upright (Figure 3.13).

The patient is positioned using laser beam markers to ensure they are centred correctly within the machine (Figure 3.14). A cone shaped X-ray beam is utilized, and during a single rotation of the X-ray source and detector around the patient, a series of 2D projections is obtained. This process is illustrated

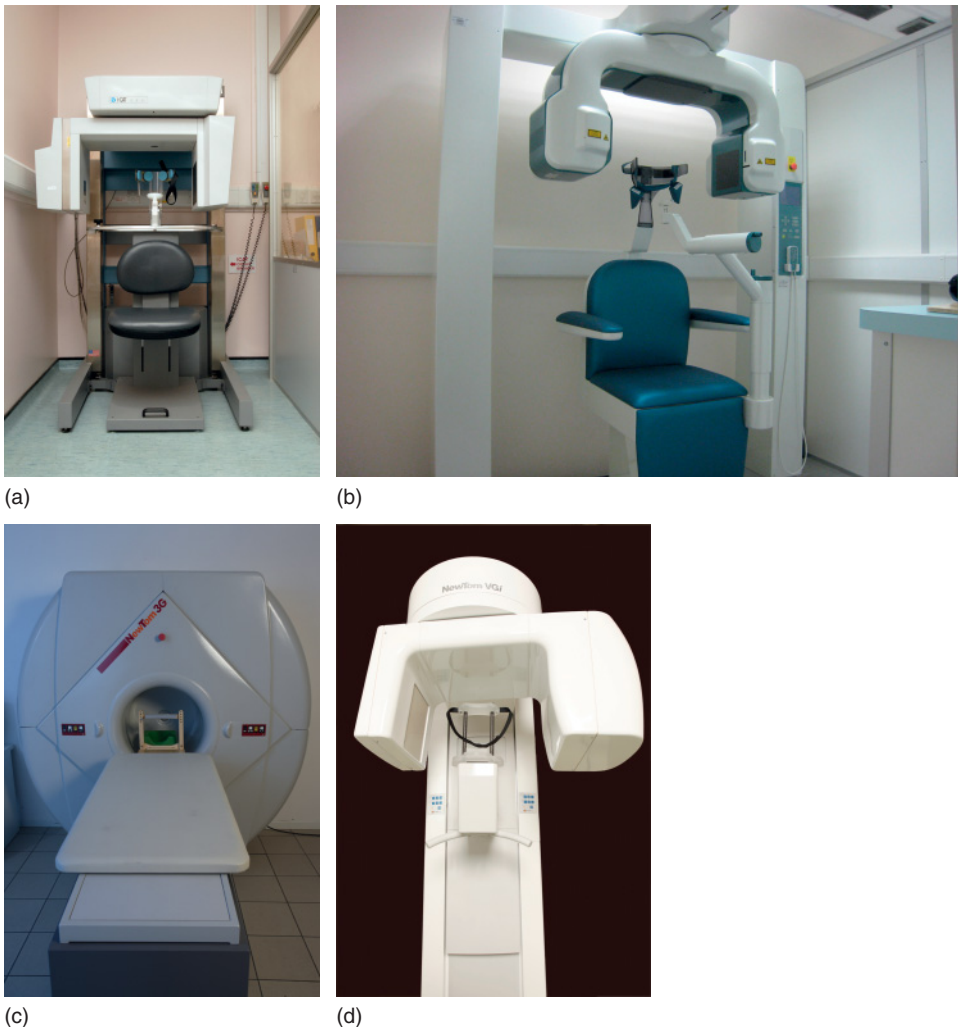


Figure 3.13 Examples of cone beam computed tomography units. (a) The Classic i-CAT (With permission from Imaging Sciences International, Hatfield, PA, USA and Cardiff University, UK). (b) The 3D Accuitomo (J. Morita Mfg. Corp., Kyoto, Japan). (With permission from the manufacturer (GmbH), courtesy of Eric Whaites, Department of Dental and Maxillofacial Radiological Imaging, King's College London, UK.) (c) The NewTom 3G (QR srl, Verona, Italy). (With permission from QR srl (Quantitative Radiology).) (d) The NewTom VGi (QR srl, Verona, Italy). (With permission from QR srl (Quantitative Radiology).)

in Figures 3.15 and 3.16. For a “standard” scan using the Classic i-CAT (Imaging Sciences International, Hatfield, PA, USA), 306 projections are acquired, but if a higher resolution is required 599 projections are obtained. The data from these projections are reconstructed using sophisticated algorithms similar to those used in conventional CT to produce a volumetric dataset.

This process, known as primary reconstruction, can take several minutes to perform and is partly dependent upon the number of projections obtained and the processing power of the PC used. Secondary

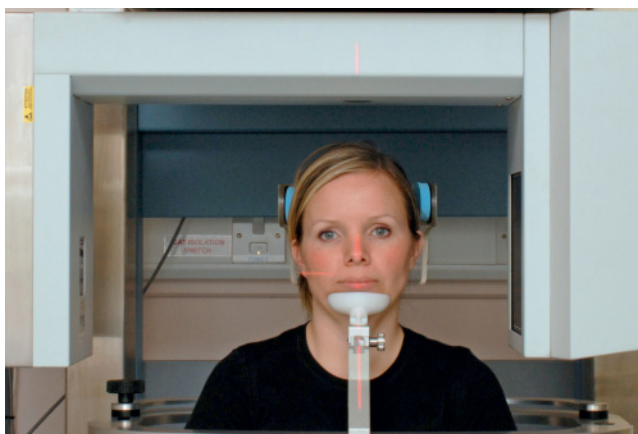


Figure 3.14 Correct positioning of the patient for cone beam computed tomography scanning is attained using a series of laser beam markers and stabilization aids such as a chin cup. (With thanks to Nicola O’Kelly.)

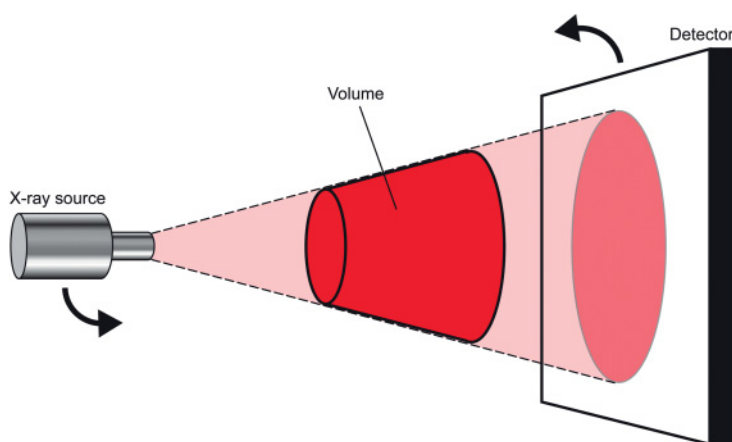


Figure 3.15 Diagram showing the cone shaped X-ray beam used in cone beam computed tomography. A single rotation of both the X-ray source and the detector around the patient produces the “volume of interest,” which can then be reconstructed. (With permission from Cardiff University, UK.)

reconstruction is, however, extremely fast and generally results in images in the axial, coronal, and sagittal planes (Figure 3.17). In addition, multiplanar reformatting into other clinically useful planes is also possible. These include panoramic type views, cross-sections through the jaws, and corrected lateral views of the TMJ.

Although the reconstruction time is quite long, the scanning time is quick (10–40 seconds), which is an advantage, particularly when scanning children, as it helps to reduce the chance of movement artifacts. Paradoxically, movement artifacts are more common with CBCT than with conventional CT.⁴⁹ Stabilization

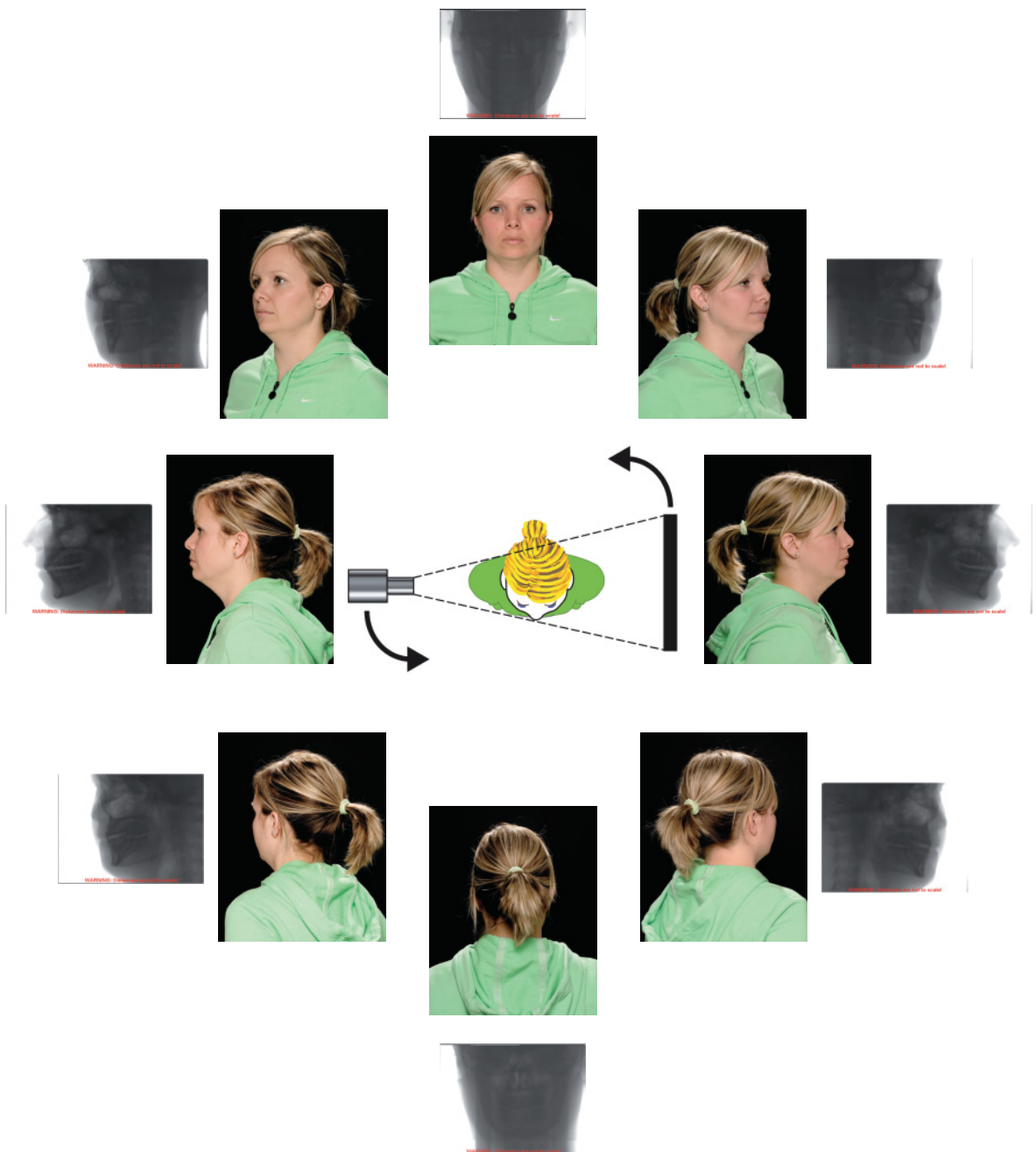


Figure 3.16 During the rotation, a series of projections is obtained. In this illustration, eight projections are shown, although in reality several hundred are acquired. The photographs show the view of the patient “as seen” from the X-ray source, along with the resultant projection image. (With permission from Cardiff University, UK, and thanks to Nicola O’Kelly. Projections used with permission from Imaging Sciences International.)

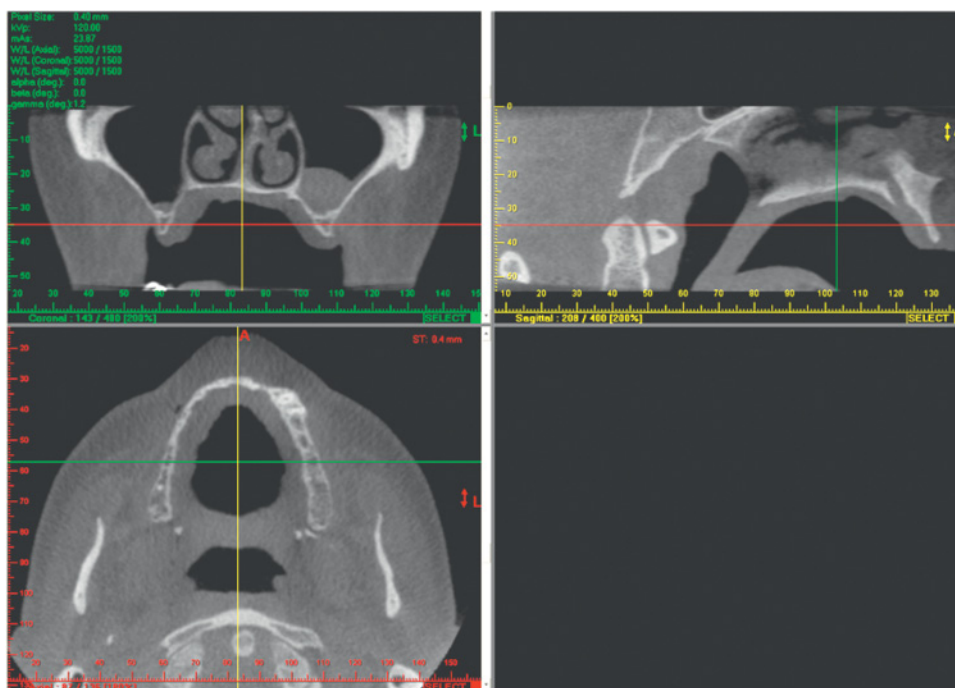


Figure 3.17 Example of a secondary reconstruction into axial, coronal, and sagittal planes. The green, red, and yellow lines allow easy cross-referencing between images. (With permission from Imaging Sciences International.)

aids such as biteblocks, chin cups, and head straps may help reduce movement, but their use can alter the soft tissue morphology, which can be an important consideration.

There are three categories of CBCT scanner: large field of view (FOV), medium FOV, and small FOV scanners.⁵⁰ The *large-volume* scanners are capable of scanning the whole facial skeleton, the *medium-volume* ones are used to scan both jaws together, whereas the *small-volume* scanners are well suited for imaging single jaws, small sections of the facial skeleton, and small groups of teeth. Therefore the clinical applications for these machines are different. The differences between the machines are becoming less distinct as several manufacturers now produce machines that will perform scans using all three FOVs.

Performance and accuracy

CBCT shows the bone and teeth well, but amalgam produces artifact that can degrade the image, although this is often less severe than with conventional CT (Figure 3.18).⁴⁹

Spatial resolution – the ability to distinguish two structures close together

The voxels within the volume recorded are isotropic (cubic) and can be much smaller than conventional CT, in the range 0.125–0.4 mm³. These features help to ensure excellent spatial resolution in all planes. The spatial resolution for the small-volume units is over two line-pairs per millimeter (at 10%), and may

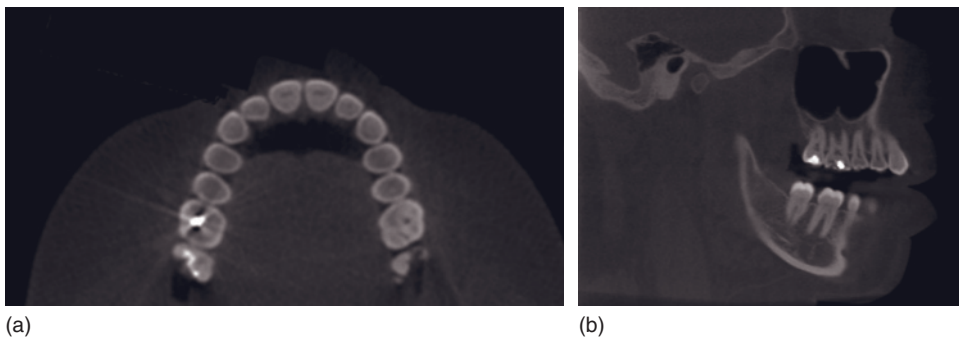


Figure 3.18 Axial (a) and sagittal (b) sections through the maxillary teeth. The amalgam restorations in the upper right first and second molars cause less severe artifacts than on conventional computed tomography. However, they do cause a radiolucent artifact in the adjacent teeth that can mimic dental caries. (With permission from Imaging Sciences International.)

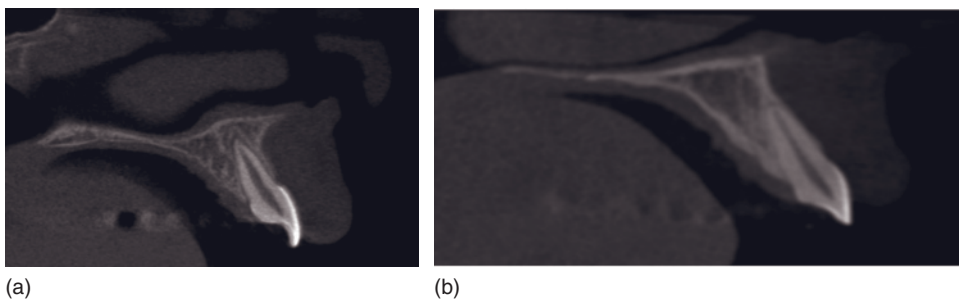


Figure 3.19 Sagittal reconstructions through the incisor region (of different patients). Image (a) was obtained with a longer exposure (more projections obtained) and reconstructed using a 0.2mm voxel size, and the image appears sharp. Image (b) was obtained using a shorter exposure time (fewer projections obtained) and reconstructed using a larger voxel size. The resultant image appears less sharp, but at a lower dose to the patient. (With permission from Imaging Sciences International.)

become as high as four line-pairs per millimeter in the near future. In practical terms, if a voxel size of 0.2mm is chosen in the scanning parameters, high-contrast objects 0.4mm or greater in size should be detected. The resolution is dependent on the scan parameters selected (time, milliampère, and kilovoltage), as well as the construction voxel used (Figure 3.19).

Contrast resolution – the ability to distinguish adjacent structures that have only small differences in density

Cone beam systems have low contrast resolution, and it is therefore not possible to differentiate between the soft tissue structures (Figure 3.20). Although this is a limitation of these systems, it should be remembered that these machines were designed specifically to image the hard tissues.



Figure 3.20 Axial section through the orbital region. The bone is shown well, but there is poor differentiation of the soft tissues. Compare this image with Figure 3.4 (conventional computed tomography), in which all the various soft tissue types can be identified. (With permission from Imaging Sciences International.)

Quantitative measurements

Conventional CT is established as a tool for accurately measuring bone density. This is useful when assessing the quality of the bone prior to the placement of dental implants. In a cadaver study, CT and CBCT density measurements were measured at mandibular implant sites. The results showed good correlation, although the CBCT values were generally higher.⁵¹ Other workers have developed regression equations for the estimation of BMD from Hounsfield numbers.⁵² In addition, the relationship between Hounsfield numbers and density was not found to be affected by the position of the object within the scanner.⁵³

However, in another study using a different scanner, a simple phantom containing acrylic sheets of uniform density was scanned. The measured Hounsfield numbers across the sheet in an anterior–posterior direction showed marked variation, with the highest measurements at the back and the lowest at the front.⁵⁴ This phenomenon has been recognized clinically where similar tissues in different parts of the image have different bone density readings.²⁸ Therefore, caution should be used when trying to assess bone density using CBCT.

Linear measurements

In an early study using a geometric phantom and the NewTom 9000, an assessment of width and height measurements was made on axial and reconstructed images. The difference observed between the measured and the actual measurements was 0.8–1% for width measurements and 2.2% for height measurements.⁵⁵ Another phantom study also concluded that the geometric accuracy of this machine was excellent, with any deviation in measurements being smaller than the resolution of the system.⁵⁶

CBCT has been used to accurately measure bone thickness in the glenoid fossa.⁵⁷ It is also accurate for measurements of periodontal bone levels and has the obvious advantage of 3D visualization of bony defects.⁵⁸ In a clinical study, the width of unerupted teeth was measured prior to their extraction. Small-FOV CBCT slightly overestimated the width of the crowns, but the error was within one pixel width (0.125mm), and this difference is unlikely to be significant clinically.⁵⁹ Another study showed that the error made on measurements from reconstructed panoramic-type images was less than 1.2%. When these measurements were performed on the axial images, the error was even smaller, at 0.6%.⁶⁰

In a different study, dried skulls were scanned in the NewTom 9000, and linear measurements obtained using the QR-DVT (QR srl, Verona, Italy) software were compared with recordings from digital callipers.⁶¹ Several sites in the maxillofacial complex were examined, and CBCT slightly underestimated the dimensions, although this difference was not significant. However, several distances in the skull base, including measurements between points on the sella turcica, were significantly smaller than those obtained using the digital callipers. The authors concluded that this was to be expected since the machine was not designed for the skull base, but they did not offer an explanation as to why this happened. This is unfortunate since this finding could have some bearing on orthognathic planning.

Another group investigated the accuracy of linear measurements between orthodontic landmarks on 3D-rendered images produced using two different CBCT units and found that the accuracy was excellent, with less than a 1% error difference between the measurements taken from the images and the actual physical measurements.⁶²

Overall, then, it can be concluded that measurements using CBCT are generally geometrically accurate and reliable, and are suitable for most requirements. Further work needs to be carried out to assess the accuracy of measurements around the skull base.

Radiation dose

One of the major advantages of CBCT over conventional CT is the reduced radiation dose. Recently, the recommendations of the International Commission on Radiological Protection regarding dose calculation were agreed.⁶³ These recommendations now include the salivary glands and the oral mucosa as weighting factors in the calculations, so the doses calculated using this method are inevitably higher than previous estimates. A summary of dose calculations from various studies is shown in Table 3.2.

The comparison between the various CBCT examinations and panoramic radiography is useful since panoramic radiography is an established imaging technique used in orthodontic diagnosis. The main risks of radiography are the somatic stochastic effects, that is, fatal and nonfatal cancers. Using a nominal fatal cancer risk of 5% per Sievert as suggested by the International Commission on Radiological Protection, the risk of developing a fatal cancer due to a single CBCT scan of the jaws is in the region of 1 in 100,000 to 1 in 350,000.⁶⁴

It should be remembered that this risk is calculated for an adult aged 30 years, and there is a latent period of several years before an effect may manifest itself. In many cases, patients undergoing CBCT are children and the risk will be higher. This is because the tissues are more radiosensitive and the child is more likely to live to see the detrimental effect. For instance, if the child is under 10 years of age, the risk is estimated to be three times that of an adult aged 30.

Clinical applications

The volumetric data produced in CBCT may be used to produce cephalometric images (lateral and posteroanterior views) using ray-sum methods. This produces accurate cephalometric images with no

Table 3.2 Comparison of effective doses from cone beam computed tomography scanners

Technique	Effective dose (μSv)	Dose as a multiple of single panoramic image	Equivalent natural background radiation dose in the UK (in days)
Large field of view (>15 cm)			
NewTom 3G (QR, Verona, Italy) ⁶⁴	68	5.1	11.3
Next Generation i-CAT (Imaging Sciences International, Hatfield, PA, USA) portrait mode ⁵⁰	74	5.6	12.3
Classic i-CAT (Imaging Sciences International, Hatfield, PA, USA) ⁶⁵	182	13.7	30.2
Medium field of view (between 10 and 15 cm)			
Next Generation i-CAT "standard" scan ⁵⁰	69	5.2	11.4
GALILEOS default exposure (Sirona, Charlotte, NC, USA) ⁵⁰	70	5.3	11.6
Classic i-CAT ⁶⁵	110.5	8.3	18.3
Small field of view (<10 cm)			
Classic i-CAT – maxilla ⁶⁵	36.5–68.3	2.7–5.2	6.1–11.3
Classic i-CAT – mandible ⁶⁵	75.3–148.5	5.7–10.9	12.5–24.6
Accuitomo (J Morita MFG Corp, Kyoto, Japan) ⁶⁶	11–77	0.8–5.8	1.8–12.8
Panoramic radiograph⁶⁷	13.3	1	2.2

magnification or distortion of the image. An example of such a cephalometric radiograph is shown in Figure 3.21. Although this is an improvement on conventional radiography, the full potential of CBCT is not being realized since the 3D data are being converted back to a 2D image.

The data can be used in 3D osteotomy and distraction osteogenesis planning software programs (Figure 3.22). These programs have been used to assess postoperative changes following osteotomies and appear to produce a valid and reproducible assessment of the craniofacial structures.⁶⁸ Superimposition of successive scans using the cranial base as a baseline can be used to locate and quantify 3D changes including rotations following surgery.^{69,70} Like conventional CT, CBCT has also been used to assess maxillary clefts. It provides 3D information on the cleft, any subsequent bone graft and the related dentition (Figure 3.23).^{71,72}

Since CBCT has low contrast resolution, the muscular morphology cannot be assessed, and MRI should be considered if this information is required. However, boundaries between soft tissue and air can be seen so CBCT has been used to assess the airway.⁷³ This has significance as it has been shown that patients

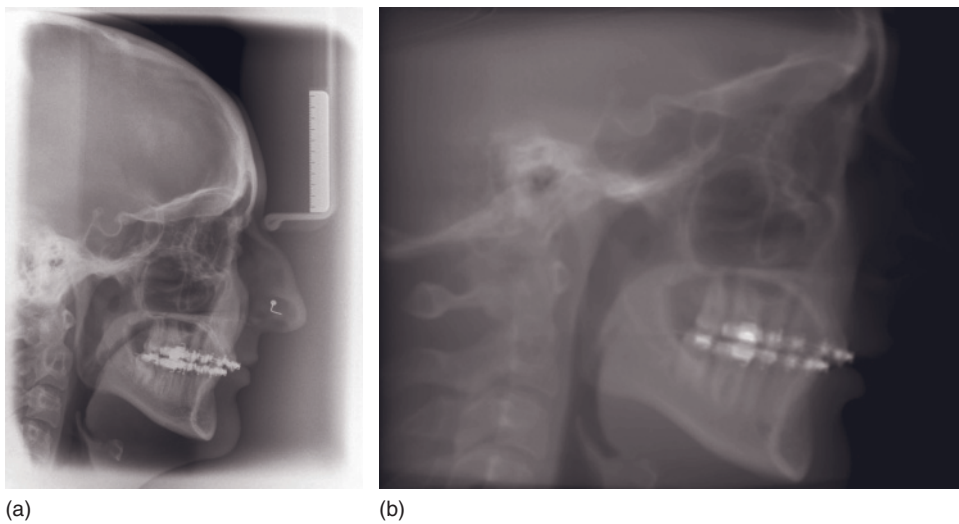


Figure 3.21 Examples of cephalometric radiographs produced by different methods. (a) Conventional cephalometric radiograph and (b) Reconstructed cephalometric radiograph produced by ray-sum methods with no distortion. (With permission from Imaging Sciences International.)

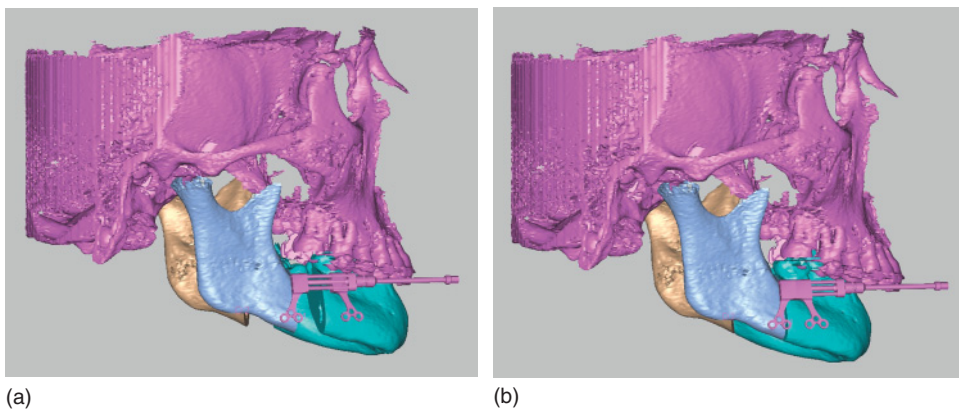


Figure 3.22 An example of a planned osteogenesis distraction case. (a) The proposed site for the distraction device. (b) The predicted outcome. (©Materialise Dental NV – SimPlant®. With thanks to Mr Alan Bocca for carrying out the reconstructions.)

with enlarged adenoids have a different facial profile from unaffected individuals. Cephalometric radiographs can only assess the area of the airway, whereas CBCT can be used to assess volume. CBCT has also been used to assess the airway in patients with obstructive sleep apnea,⁷⁴ and it may help in the management of these patients. Caution should be taken when assessing airway shape since in some CBCT units the patient is scanned sitting up, whereas in others the patient is supine: the airway shape will change depending on the patient's position.

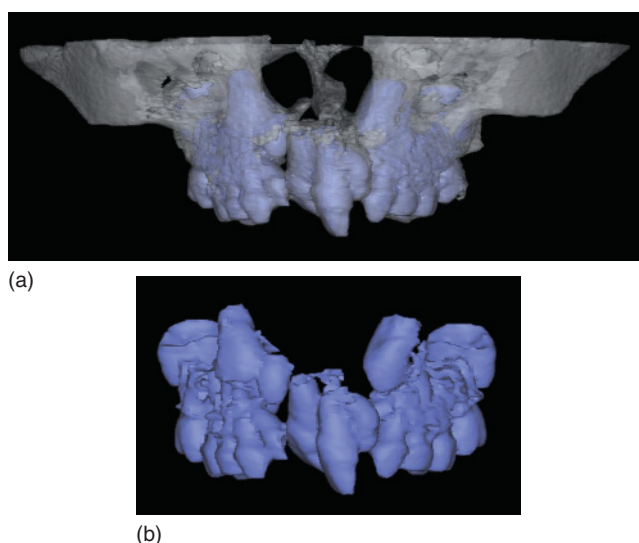


Figure 3.23 Three-dimensional reconstruction of the maxilla showing bilateral clefts in the alveolus. (a) The bone has been made translucent to allow the visualization of the dentition. (b) Three-dimensional reconstruction of the teeth. (©Materialise Dental NV – SimPlant®.)

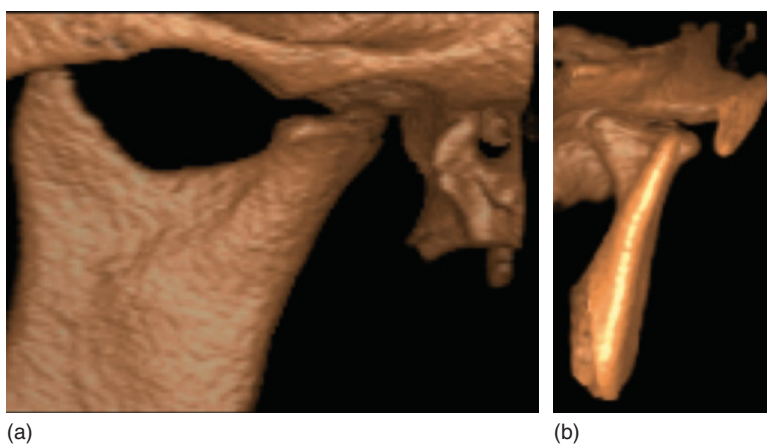


Figure 3.24 Three-dimensional reconstructions of the left temporomandibular joint showing marked flattening of the condyle: (a) lateral view and (b) frontal view. (With permission from Imaging Sciences International.)

Although MRI is considered to be the “gold standard” as far as TMJ imaging is concerned, CBCT shows the bony component very well (Figure 3.24), and some studies have shown it to be more accurate than conventional CT.⁷⁵ 3D reconstructions are helpful if there are severe morphologic abnormalities present or if surgery is being planned. CBCT is considered by some to be the method of choice for imaging bony abnormalities such as ankylosis or bony tumors.⁷⁶ In addition, the technique may be used in claustrophobic patients and in those patients with pacemakers or ferromagnetic foreign bodies. Air-contrast

arthrography has been reported, which provides limited information on the articular disc and may prove to be a useful technique in some patients.⁷⁷

CBCT is also proving valuable in the 3D assessment of bone prior to implant placement (Figure 3.25),⁷⁸ and it is encouraging that guidelines have been produced to help in the selection of appropriate radiographs.⁷⁹

CBCT can be used to assess severe facial trauma (Figure 3.26).⁸⁰ It can also be used following osteotomy if there has been an unfavorable sagittal split when information regarding the position of the mandibular condyle is required (Figure 3.27). Other applications include the assessment of disease affecting the maxillary antrum, including cysts and benign tumors (Figure 3.28).

It is possible to trace the inferior dental canal using software programs. This may prove valuable in the assessment of impacted teeth where there is a suspicion that the tooth is intimately associated with

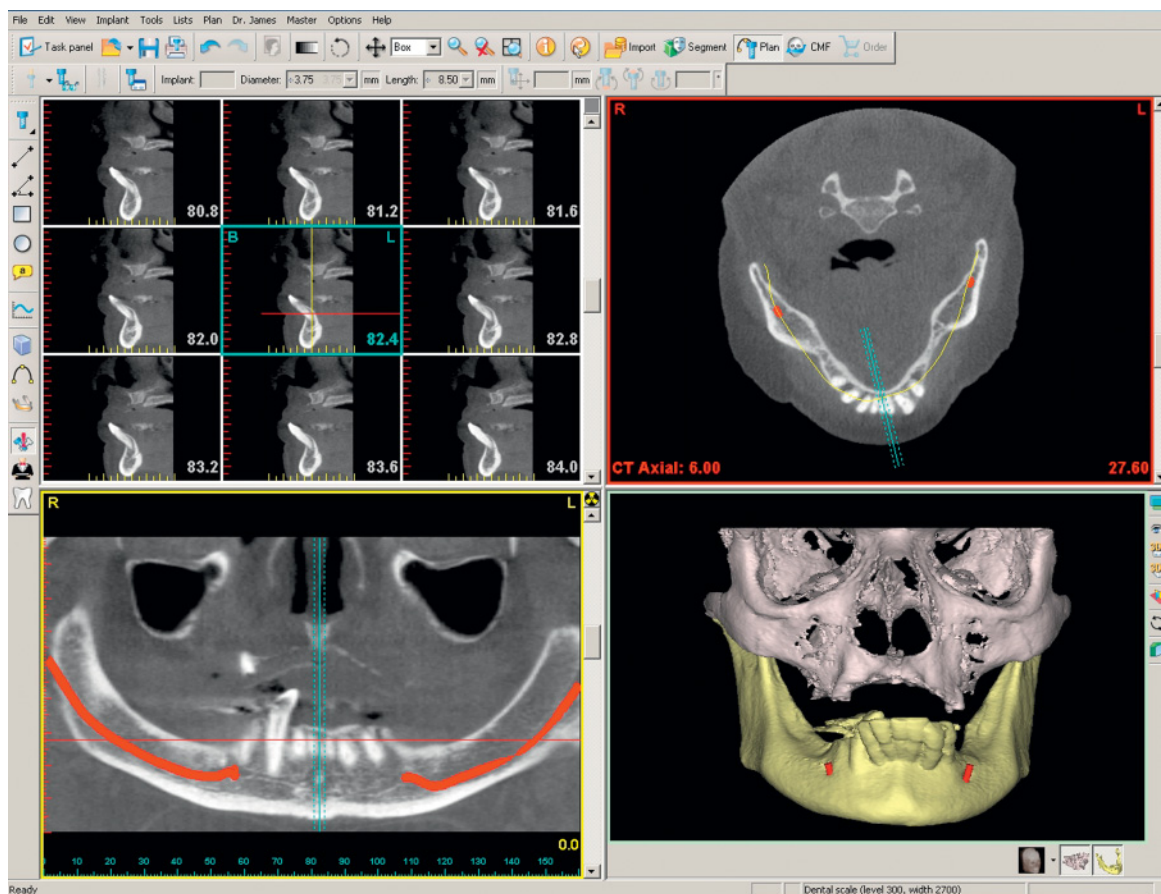


Figure 3.25 Example of an implant planning software program. The four panes show the axial, panoramic, cross-sectional, and three-dimensional reconstructions of the mandible. The inferior dental canal has been mapped in red. (©Materialise Dental NV – SimPlant®.)

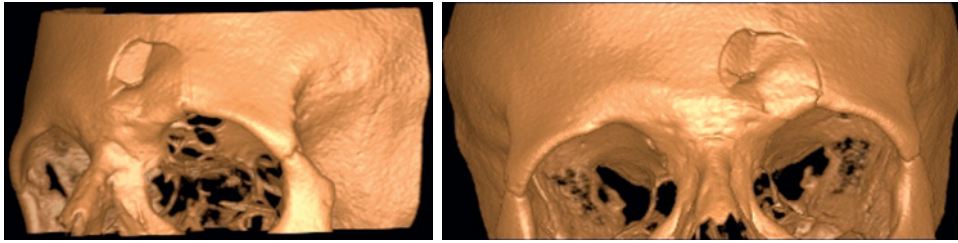


Figure 3.26 Three-dimensional reconstructions showing a depressed fracture of the outer table of the frontal bone. (With permission from Imaging Sciences International.)

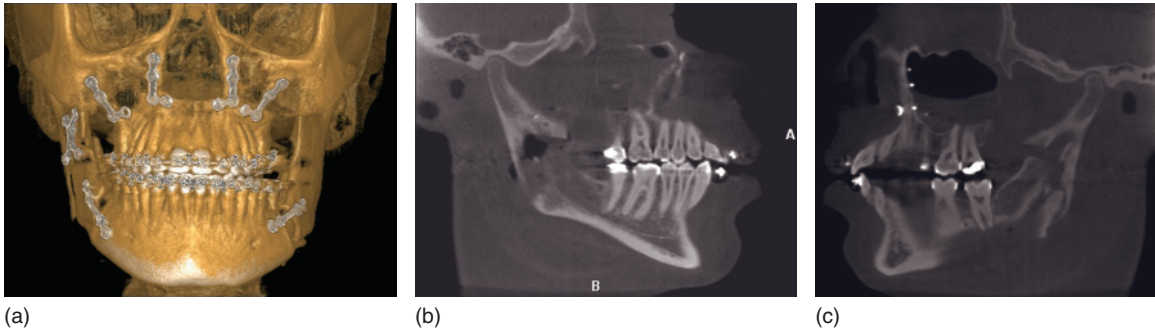


Figure 3.27 Three-dimensional reconstructions of the jaws immediately following an osteotomy. There had been an unfavorable split on the right side, and the scan accurately confirms the position of the fragments and the position of the titanium plates (a). (b, c) Corrected lateral slices through the condyles confirming the correct position of the condyles within the glenoid fossae. (With permission from Imaging Sciences International.)

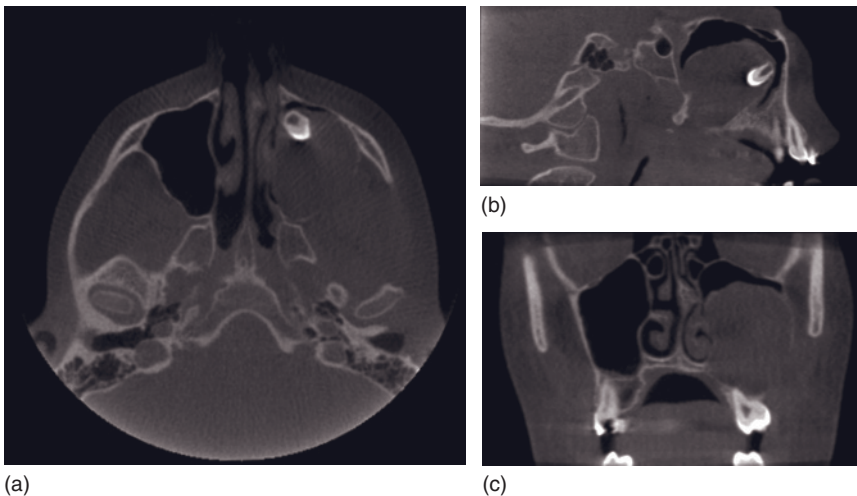


Figure 3.28 Axial (a), sagittal (b), and coronal (c) sections through the left maxillary antrum showing a large odontogenic keratocyst associated with a displaced unerupted third molar tooth. These images show the full extent of the lesion and demonstrate expansion of the antrum by the lesion. (With permission from Imaging Sciences International.)

the canal (Figure 3.29).^{81,82} Impacted teeth are demonstrated well on CBCT. Root morphology, root resorption, angulation, and spatial relationship to other structures are clearly shown, which helps the orthodontist in planning treatment and helps to minimize damage to adjacent teeth if surgical removal is necessary (Figure 3.30).^{83,84} Dental anomalies such as invaginated teeth (Figure 3.31) and supernumerary teeth may also be demonstrated.⁸⁵

Although CBCT uses a lower dose than conventional CT, it should not be used routinely to assess the orthodontic/orthognathic patient. Most of the papers concerning its clinical use are small studies or case

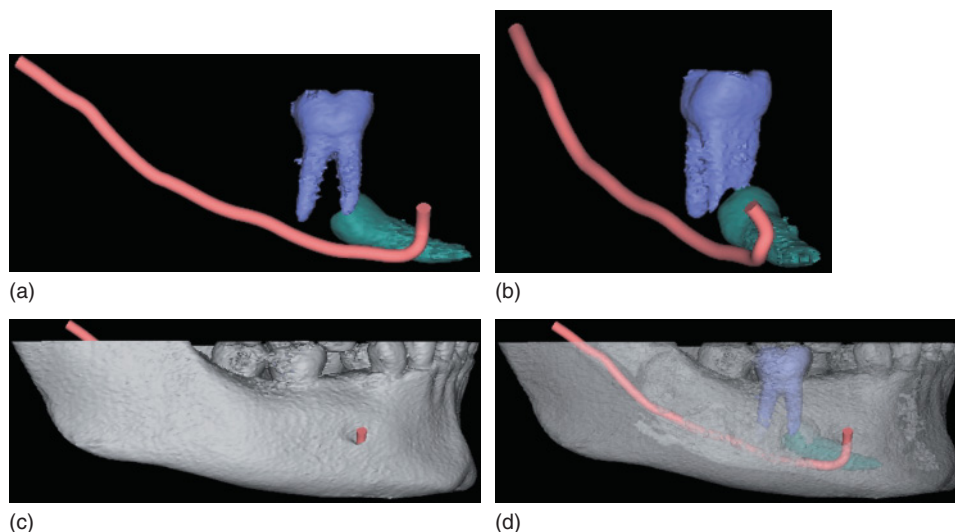


Figure 3.29 Three-dimensional reconstructions showing the intimate relationship between the lower right unerupted second premolar tooth and the inferior dental canal (IDC). In addition, the mesial root of the lower right first molar has also been resorbed. (a) Three-dimensional reconstruction of the mandible with the IDC mapped. (b) Following segmentation of the lower left right molar and lower right second premolar with the structures made transparent. (c) Lateral view following subtraction of the overlying mandible from the display. (d) Frontal view following subtraction of the overlying mandible from the display. (©Materialise Dental NV – SimPlant®.)

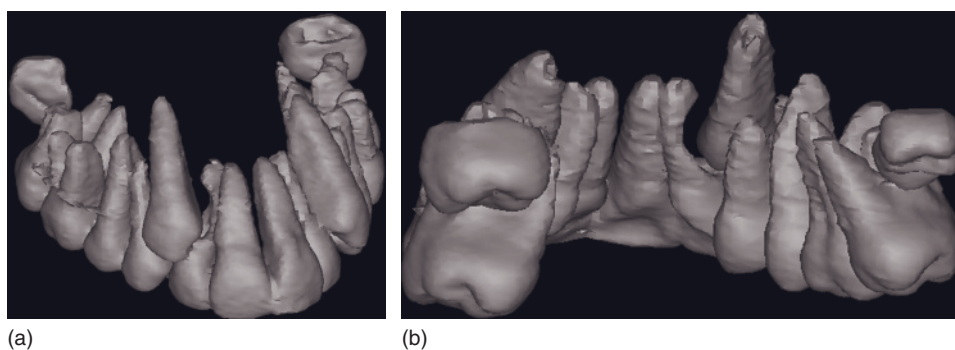


Figure 3.30 Three-dimensional reconstruction showing marked resorption of the upper right lateral incisor by the impacted canine: (a) frontal view and (b) posterior view. (©Materialise Dental NV – SimPlant®.)

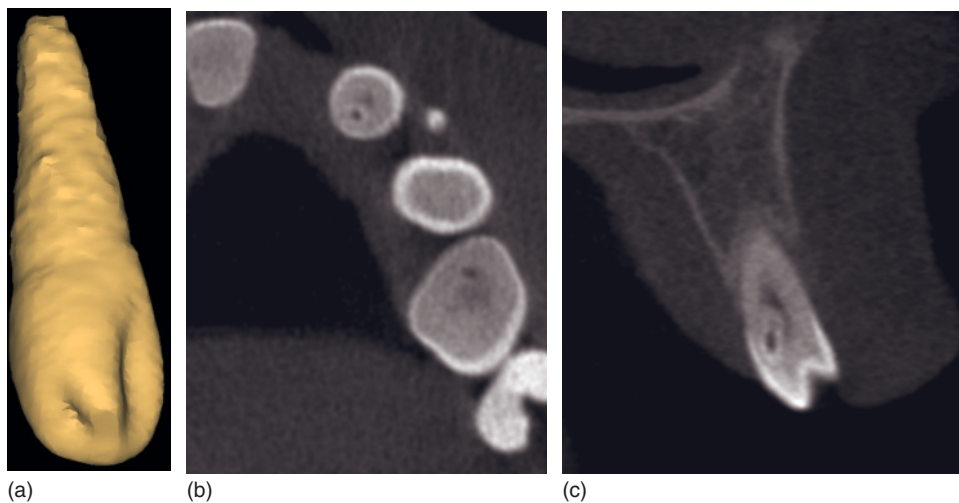


Figure 3.31 (a) Three-dimensional reconstruction of an incisor tooth with a large talon cusp. (©Materialise Dental NV – SimPlant®.) The axial (b) and sagittal (c) cross-sectional images through the tooth also show the presence of an enamel invagination. (With permission from Imaging Sciences International.)

reports. The British Orthodontic Society has suggested the following clinical situations where CBCT may be useful:⁸⁶

- where conventional radiography does not supply the diagnostic information required;
- in cases of cleft palate;
- for the planning of orthognathic surgery;
- for assessment of root resorption;
- for assessment of unerupted tooth position, especially where resorption is a concern.

In addition, the European Academy of Dental and Maxillofacial Radiology has agreed 20 basic principles for the use of CBCT.⁸⁷ In the future, a group known as SEDENTEXCT (Safety and Efficacy of a New and Emerging Dental X-Ray Modality) hope to produce evidence-based referral guidelines for its use. In the meantime, CBCT should only be performed where the benefit will outweigh the risk.

MAGNETIC RESONANCE IMAGING

MRI has been widely used in medicine for many years and complements other forms of cross-sectional imaging. Compared with CT, described above, it has better soft tissue contrast but is generally less well suited to demonstrating bony abnormalities.

Basic principles

A full account of the principles of MRI is beyond the scope of this book. For a comprehensive description on this subject, the reader should refer to specialized texts dealing with the physics and

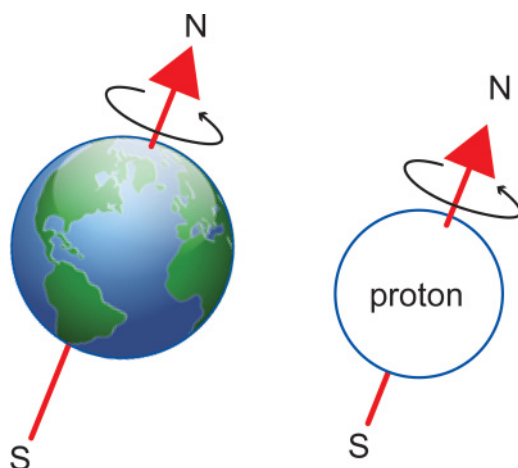


Figure 3.32 Diagrammatic representation of a spinning proton compared with a spinning Earth. The curved arrow denotes the direction of spin around the axis. The straight arrow represents the axis of spin, which is also the direction of the magnetic field. (With permission from Cardiff University, UK.)

techniques of MRI. An appreciation of the basic principles of MRI is helpful with interpretation, but the concept of how the images are formed can appear complex and involves some knowledge of physics.

Medical MRI involves imaging hydrogen, or to be more precise the nuclei of hydrogen atoms, which are protons. Like the Earth, a proton rotates on an axis (Figure 3.32), that is to say, it possesses *spin*, and its inherent positive charge also spins with it. The laws of electromagnetism state that when a charged particle moves, a magnetic field is created. Because each nucleus is a positively charged proton that spins, it generates a magnetic field; in other words, it behaves as a tiny magnet.

When these tiny magnets are placed in a strong magnetic field, they change from a haphazard orientation to align with the direction of the main magnetic field (B_0 ; Figure 3.33). However, protons behave differently from bar magnets in that some line up in the same direction as the magnetic field (parallel), whereas a slightly smaller number align in the opposite direction (antiparallel). The net amount of magnetism produced is of the order of just a few microtesla, which is immeasurably small in the direction of the main magnetic field. However, it becomes measurable when the protons are tipped through 90 degrees (see below).

Not only does each proton spin on its axis, but it also tilts relative to the direction of the magnetic field, and wobbles or rotates with a circular motion in a similar manner to a child's spinning top or gyroscope. This secondary circular motion is called precession and is shown diagrammatically in Figure 3.34. The rate at which the precession takes place is governed by the strength of the magnetic field – the stronger the field, the faster the rate of precession. The precession rate is in fact extremely fast, being approximately 42.5 MHz (42.5 million times a second) for a field strength of 1 Tesla (1 Tesla being 20,000 times the strength of the Earth's magnetic field). This rate increases to 63.8 MHz for a 1.5 Tesla field strength, which is the typical strength of the magnets currently used in MRI scanners. These frequencies fall into the range of radiowaves, or radiofrequency (RF) radiation. At the time of writing, 3 Tesla units have become available, which improve the signal-to-noise ratio and provide better homogeneity of the image.

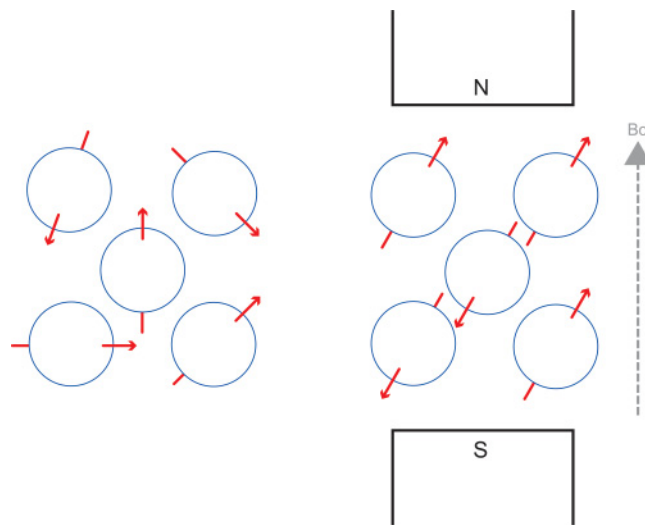


Figure 3.33 Protons change from a random orientation (left) to align with the applied magnetic field (B_0 ; right), either parallel or antiparallel. (With permission from Cardiff University, UK.)

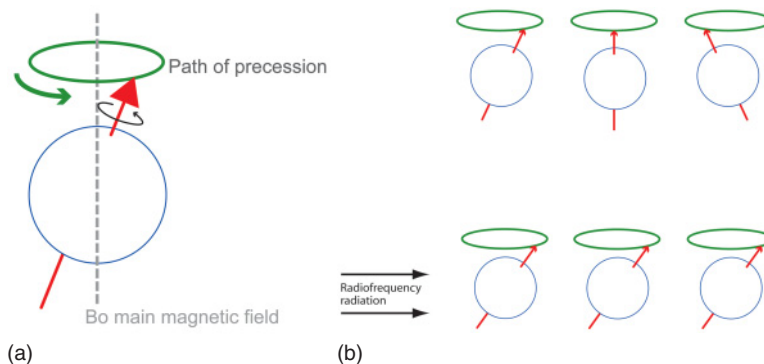


Figure 3.34 (a) The rotating proton spins on its axis (black curved arrow) and also precesses like a gyroscope (green curved arrow). The application of resonant radiofrequency radiation causes protons to precess in phase. Before (b, top) and after (b, bottom) application of the resonant radiofrequency radiation. (With permission from Cardiff University, UK.)

So far the effect of a magnetic field on a spinning proton has been outlined, this being the magnetic component of MRI. The next concept to be discussed is that of *resonance*. Resonance occurs when an object is exposed to a frequency that is similar to that of its own inherent frequency. If a pulse of RF radiation of the same frequency as that of the precessing protons is applied, the protons precess in phase. The RF pulse also causes the net magnetism to move from its alignment with the magnetic field B_0 , the extent being governed by the duration and intensity of the RF pulse. If the RF pulse is sufficiently long or intense,

the magnetism will flip through 90 degrees so that it can be measured by a coil of wire whose axis is also at 90 degrees to the direction of B_0 . This may be the same coil that was earlier used to produce the RF pulse, that is, it is being used as both receiver and transmitter.

When the RF is switched off, the protons start to dephase and realign in the direction of B_0 , and in doing so lose energy, a process called relaxation. This means that the amount of magnetism in the longitudinal direction (that of B_0) increases (recovers), and that in the transverse plane (at 90 degrees to B_0), decreases (decays). The energy loss is detected as a radio signal by the receiver coil and is referred to as free induction decay.

This energy is lost to the surroundings (or lattice), and the rate at which this occurs is characterized by T1 and is called the longitudinal relaxation time or spin-lattice relaxation time. The relaxation depends on the ability of the protons to transfer their energy to their environment and varies between different types of tissue. Tissues with a short T1 produce a high-intensity (white or bright) signal on a T1-weighted image, and those with a long T1 produce a low (black or dark) signal.

As the protons dephase, the amount of transverse magnetism decreases. The rate of decay is characterized by a time constant T2, called the transverse relaxation time or spin-spin relaxation time. On a T2-weighted image, tissues with a long T2 generate a high (bright)-intensity signal and those with a short T2 produce a low (dark) signal.

The narrative described above explains the effect of MRI following a single 90 degree pulse, but when imaging patients a sequence of RF pulses is employed, and some of these approaches are described below.

Imaging sequences

So, in MRI, one is basically imaging hydrogen, which is found in abundance in the soft tissues, but the way in which the hydrogen protons behave varies from tissue to tissue and with the imaging sequences used. For example, hydrogen is found in both water and fat. However, the hydrogen nuclei in these two substances have different values for T1 and T2 and thus can be regarded as contrasting substances.

Imaging protocols are chosen to create image contrast and thus show tissues in different ways to assist with diagnosis. A T1-weighted image generally shows the anatomy well, and on this sequence fat has a high signal (appears bright) and water a low signal (appears dark). On a T2-weighted image, water has a high signal, so this sequence will demonstrate cysts, inflammation, and malignant tumors, as these have relatively high water content.

The most common pulse sequence is the spin-echo sequence. This comprises a 90 degree pulse followed by a 180 degree pulse, which rephases the protons and creates a radio signal known as an echo. The sequence is repeated many times. Its sequence is characterized by the duration of the RF pulse repetition time (TR) and the time to echo (TE). The TR is the time between the application of the 90 degree pulses, whereas the TE is the time from the 180 degree pulse to the peak signal received in the coil (Figure 3.35). Different image weighting is obtained by varying the duration of TR and TE.

In a T1-weighted image, contrast is produced mainly by the T1 differences between fat and water, but also by how much fat and water the tissues contain. So, for example, the salivary glands, which contain fat, appear brighter than muscle, which has less fat. To produce a T1-weighted image, a short TR, usually of less than 500 milliseconds, is used together with a short TE (usually less than 30 milliseconds).

A T2-weighted image uses a long TR, usually greater than 1500 milliseconds, and a long TE, usually more than 80 milliseconds. To improve the water signal, the TR time may be extended up to 4000 milliseconds, as might be used in MRI sialography for example.

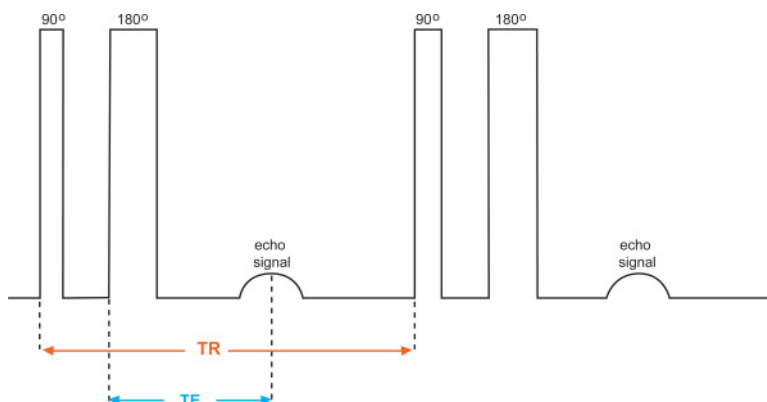


Figure 3.35 Diagrammatic representation of a spin-echo pulse sequence. Note that the diagram shows a sequence in which the signal has the same intensity (same height) but a different duration (different width). TE, time to echo; TR, repetition time. (With permission from Cardiff University, UK.)

A proton-weighted image diminishes both T1 and T2 effects. Thus, it has a long TR, which allows fat and water to recover their longitudinal magnetism, and a short TE, which does not give sufficient time for the transverse magnetism to decay. This sequence is commonly used to show the fibrocartilaginous disc in the TMJ.

Fat is seen on most MRI images and is a major factor in determining the image contrast and displaying or highlighting anatomic structures. However, in some circumstances, fat can obscure disease, particularly if there is low contrast between it and adjacent diseased tissue. This is especially true of T1-weighted images. In these circumstances, suppressing the fat signal aids diagnosis.

One fat suppression sequence that is commonly used is called STIR sequence, which stands for short tau (or short TI) inversion recovery. It is a variation of a spin-echo sequence in which an additional 180 degree RF pulse is introduced a time, TI, before the 90 degree pulse. Another sequence, called fat saturation or fat-sat, takes advantage of the slightly different resonance frequencies between fat and water. It has the advantage that it modifies the signal from fat while minimally affecting other signal characteristics.

Spin echo is used to produce T1-, T2- and proton density-weighted images. It is also possible to undertake a fast imaging sequence to reduce unwanted patient movement as might occur, for example, during breathing. This can be done using a gradient-echo sequence, which uses flip angles that are less than 90 degrees. So by varying the RF pulse intensities and RTs, different images sequences can be obtained.

An MRI scanner contains RF coils or “antennae” that both deliver and receive radiowaves. For detailed examinations, specialized coils are often used, like the one shown in Figure 3.36, for examining the head for example. To improve resolution, more than one set of coils can be used simultaneously.

Contrast agents

Contrast agents are used to highlight certain types of lesion by improving their contrast against the adjacent normal tissue, and they also help by increasing the signal-to-noise ratio. The most common



Figure 3.36 (a) Photograph of a typical magnetic resonance imaging machine with the head coils in place around the patient. Before scanning, the patient will be moved fully inside the tunnel of the machine. (With thanks to Nicola O'Kelly.) (b) Close-up picture of the head coils. (With permission from Cardiff University, UK.)

contrast agent is based on gadolinium, which has paramagnetic properties. It shortens T1 on T1-weighted images and enhances vascular tumors and lesions where the blood–brain barrier or blood–tumor barrier has been disrupted.

Advantages and disadvantages of magnetic resonance imaging

The main advantages are as follows:

- It has none of the risks associated with ionizing radiation.
- It has good soft tissue contrast.
- Multiplanar imaging is easily performed.
- Tissue contrast agents (chelated gadolinium compounds) are available to assist in diagnosis.

There are, however, several disadvantages:

- There is a relatively long image acquisition time, usually minutes for each sequence. This has the potential for motion artifacts, so patients must keep still to avoid image degradation. They must also stay in the same position for all of the subsequent imaging sequences during the examination.
- Some patients find the experience claustrophobic.
- There is considerable noise from the gradient coils, which are used to select the plane of imaging.
- Image artifacts occur when ferromagnetic substances are in the vicinity of the area being imaged.
- The procedure is contraindicated with most cardiac pacemakers and other implantable devices such as hydrocephalus shunts, cochlear implants, neurostimulators, and intracranial aneurysm clips. However, manufacturers are now producing implants that are compatible with MRI, although it is important to check before the examination that it is safe to proceed.
- MRI is contraindicated if there are metallic foreign bodies in the eye, for example as the result of an occupation or accident.

3D reconstruction

A single radiograph of a region of the body, such as the facial bones, shows the anatomic structures two-dimensionally. However, an indication of the spatial relationships between these structures can be obtained by taking radiographic projections at right angles to one another, by employing parallax views, or by using conventional tomography. The advent of cross-sectional imaging has made 3D imaging feasible. Until recently, 3D MRI was impractical due to the long imaging times. However, the development of fast gradient-echo imaging sequences has made the implementation of 3D imaging more practical.⁸⁸ One method of producing a 3D image is to obtain echoes from a volume of tissue while applying a phase-encoding gradient in the z-axis. With a block rather than a slice of data, it is possible to reformat the information into a 3D image. Ideally, the voxels should be isotropic to reduce the building block (staircase artifact) appearance of the 3D image.

In orthodontic treatment planning for moderate-to-severe skeletal abnormalities, 3D imaging is becoming increasingly employed to provide better graphical detail about skeletal relationships and facial asymmetry than is provided by 2D images. Traditionally, CT, and more recently CBCT, has been used to provide these data, but obtaining good quality 3D CT images requires relatively high-dose techniques. MRI, on the other hand, does not use ionizing radiation, although it is expensive, has yet to be fully evaluated for 3D imaging of the jaws, and in some centres is associated with a shortage of units to undertake routine 3D scans.

Attempts have been made to obtain 3D views of the TMJ, although these studies have been somewhat limited. As far back as 1992, an engineering design program was used to construct 3D models from MRI images taken on a 1.5 Tesla machine of a dentate dry skull with an artificial acrylic TMJ disc.⁸⁹ The model dimensions were consistent with the original, but the main limiting factor was the slice thickness, which is still an issue today.

More recently, techniques based on surface rendering have been used to assess 3D morphology and joint dynamics. Bilateral surface coils have been used to produce high-definition images from which 3D images were reconstructed with the Amira surface generation algorithm, followed by step-wise simplification and smoothing.⁹⁰ Although it was a prototype, the process was time-consuming, although it could be automated. 3D imaging is, at the time of writing, still developing, but with further improvements, particularly in the signal-to-noise ratio, it should become a more practical proposition.

Accuracy

The accuracy of 3D images of the mandible has been investigated using an imaging sequence called volumetric interpolated breath-hold examination (3D vibe).⁹¹ This sequence gave the most optimal images and showed satisfactory accuracy and image quality. Mandibular growth during orthodontic treatment on children aged 9–12 years with Class II division I malocclusions and normal occlusions has also been assessed, and it was found that assessment using 3D MRI was similar to that using other 3D techniques.⁷⁰

Magnetic resonance imaging in patients with orthodontic appliances

When placed in a magnetic field, objects are magnetized to varying degrees. For example, ferromagnetic materials such as iron and cobalt strongly amplify the magnetic field, paramagnetic substances such as aluminum slightly amplify the field, and diamagnetic materials including gold, carbon,

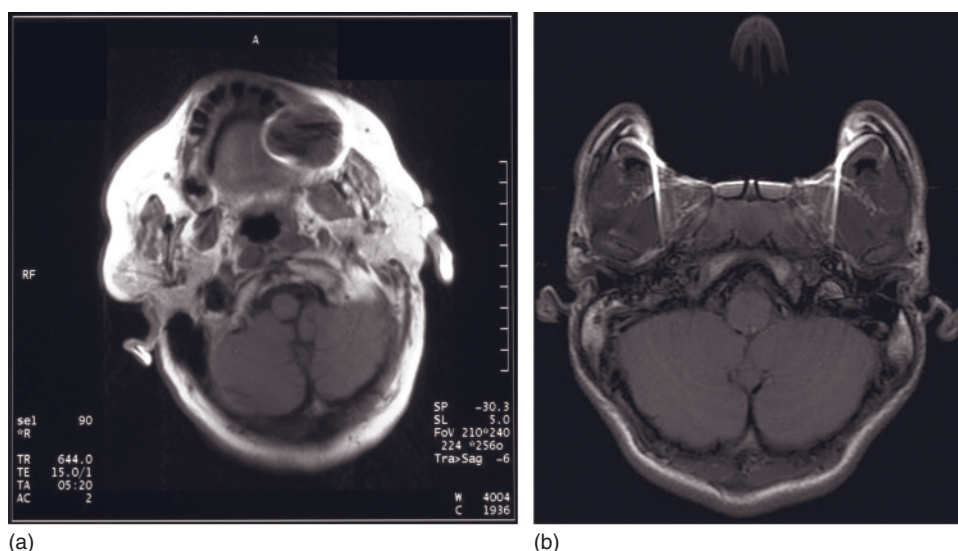


Figure 3.37 Examples of image artifacts due to metallic objects. (a) Loss of image detail caused by perturbation of the magnetic field by a stainless steel crown, causing a dark circular zone in the region of the tooth. (b) A T1-weighted axial image taken at the level of the mandibular condyles showing a loss of image of the facial bones due to stainless steel within an orthodontic appliance (With permission of Dr Helen Williams, Birmingham Children's Hospital, UK.).

copper, and zinc slightly weaken the field.⁹² Disturbance of the magnetic field by metals with magnetic properties alters the signal, resulting in an area of blackness with loss of image detail. Image artifacts can occur in patients who have intraoral metallic devices (Figure 3.37). Patients with metallic orthodontic braces may require their removal prior to MRI scans of the head, but ceramic brackets and direct bonded metal tubes with the arch wires removed do not produce significant loss of image detail.⁹³

Clinical applications

In most dental and maxillofacial disorders, sufficient diagnostic information may be obtained from plain radiographs, but where this is not the case other imaging techniques may be needed. MRI, CT, ultrasound, and other types of medical imaging are complementary to each other, although each has its own specific indications. Referral criteria have been produced by the Royal College of Radiologists for clinicians to consult when requesting diagnostic imaging for all regions of the body, including the head and neck.⁹⁴ Such guidelines provide practical advice based on the best available evidence, together with expert opinion. It is important to remember to undertake imaging only when it is likely to be contributory to the assessment or diagnosis.

The head and neck region is complex in terms of both its anatomy and the conditions that affect it. In simple terms, CT is primarily used to assess bony disorders, for example orbital wall fractures, and MRI for the soft tissues, such as salivary gland tumors or other soft tissue disease. However, CT does show the soft tissues reasonably well and MRI the bone, both being used for these purposes, and in reality challenging diagnostic issues often require more than one type of imaging.

Temporomandibular joint

Disorders of the TMJ affect either the hard tissues (bone), the soft tissues such as the capsule and disc, or both. Conditions that affect the bone, such as the arthritides, fractures, hyperplasia, and tumors, are best initially imaged with radiographs. In most instances, a dental panoramic radiograph and possibly a posteroanterior facial view is all that is required. If more detail is required, CBCT or CT may be necessary, but these radiographic techniques provide little or no information on the disc.

Internal derangement (or disc displacement) is an abnormality of the position and possibly the morphology of the disc. It is a common disorder and may result in a click on jaw movement or a limitation of mouth opening, but it should be remembered that disc displacement is also seen in asymptomatic individuals. The etiology of the condition is unknown, but it is associated with parafunction such as jaw-clenching, stress, trauma, and whiplash injury. Disc displacement has a bimodal presentation, mainly occurring at 20–30 and 50–60 years of age. Anterior displacement accounts for nearly 50% of abnormally positioned discs, followed by anterolateral displacement in approximately 30% of cases, possibly due to weakness of the lateral disc attachment.⁹⁵

In most cases, internal derangement responds to conventional treatment, such as a soft diet, occlusal splint therapy, jaw exercises, and avoidance of tooth-clenching. Although the clinical examination may suggest the presence of disc displacement, the disc is not visualized on radiographs without the use of contrast injection (arthrography), and this has been largely superseded by MRI. So when conventional treatment fails or more information is needed about the joint and the disc position, MRI should be considered. This is particularly so if surgical treatment is being contemplated.

A dedicated TMJ coil is normally used to image the TMJ. Typically, MRI imaging involves a series of 3 mm slices in a parasagittal plane, with the direction of the slices at right angles to the transverse axis of the condylar head (Figure 3.38). This may be supplemented by coronal slices, which help with the visualization of a laterally or medially displaced disc.

Proton density- or T1-weighted images together with T2-weighted images are usually performed. The proton density- or T1-weighted images are used to show the anatomy of the joint, particularly of the disc,



Figure 3.38 Axial scout view showing orientation of the slices relative to the condylar head.

which has a low signal so appears dark. Cortical bone also appears dark and outlines the cancellous bone, which has a medium-to-high signal due to its fat content. On T2-weighted images, the disc remains dark, as does the cortical bone, but fluid in the joint space has a high signal.

Normally, the disc lies on the anterior aspect of the articular surface (Figure 3.39a). As the mouth opens and the condyle rotates and translates, the disc moves with it, so by the end of the opening cycle it reduces to lie over the top of the condyle (Figure 3.39b); the figure illustrates a good range of mandibular

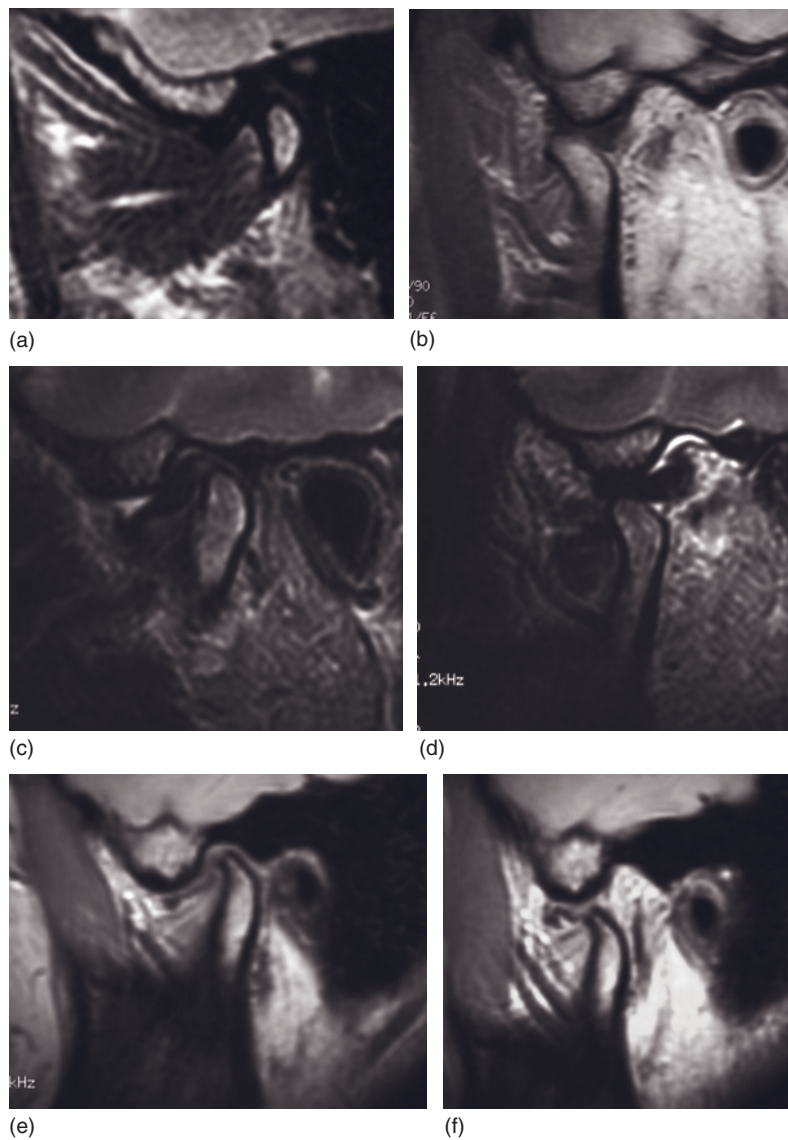


Figure 3.39 Magnetic resonance imaging scans of the temporomandibular joint in the closed and open positions, showing normal anatomy and disease. See text for details.

translation. In anterior displacement, the disc lies anterior to the condylar head (Figure 3.39c), but on opening reduces posteriorly to adopt a normal position lying over the articular surface of the condyle (Figure 3.39d); note the high signal in the latter illustration owing to joint effusion. As the disc reduces, the patient may be aware of a click. With a non-reducing disc, the disc is anteriorly displaced in the closed position (Figure 3.39e). Sometimes the disc remains anteriorly displaced during the opening cycle, and this is referred to as anterior displacement without reduction. The disc may then obstruct the forward movement of the condyle causing limited mouth opening, the disc often becoming compressed or deformed within the joint capsule (Figure 3.39e, where the disc has buckled).

The disc is usually shown well on an MRI scan, but its morphology may be altered, and if it is thinned or fragmentary, it can be difficult to identify. Careful examination of the images is required, and if the disc is not clearly seen, it may be necessary to repeat the scan sequence with a different parasagittal angulation.

When acute inflammation is present, a joint effusion may result. This is seen as fluid (high signal – white) in the upper joint space on a T2-weighted image, as shown in Figure 3.39 (middle row). Similarly, if the bone is affected by inflammation, the marrow of the condyle will have a high signal on the T2-weighted scans.

MRI has largely replaced arthrography to assess disc position, but there are limited data to demonstrate the effectiveness of this type of imaging. An exhaustive literature review highlighted a need for high-quality studies on the diagnostic efficacy of MRI in TMJ disease.⁹⁶

Vascular abnormalities

Vascular abnormalities are a diverse group of lesions. They can be classified as falling into two categories: hemangiomas and vascular malformations. However, there are other conditions that can also be regarded as vascular lesions, such as juvenile nasopharyngeal angiofibromas, paragangliomas (e.g., carotid body tumors), angiosarcomas, and Kaposi's sarcoma.

Hemangiomas usually present during the first months after birth, rapidly enlarge, and usually resolve by the end of the first decade of life. Most affect girls and are single entities. They are classified as high-flow lesions and are usually well defined. The solid part of a hemangioma is isointense with muscle on T1-weighted images, has a higher signal with T2-weighted images, and enhances with contrast.

Vascular malformations usually present later than hemangiomas during early childhood and, unlike hemangiomas, tend not to resolve with time. They are classified on the type of vessel that is abnormal into capillary, arterial, and venous malformations. Capillary and venous malformations are low-flow abnormalities, whereas the arterial types are high-flow lesions. Venous malformations commonly occur in the facial region where they often involve muscle. They may be initially diagnosed on plain radiographs due to the presence of phleboliths; Figure 3.40 shows one such lesion found on a dental panoramic radiograph taken on a patient undergoing an orthodontic assessment. The lesion was assessed with MRI to confirm the diagnosis, demonstrate its location, and show its full extent. On T1-weighted images, vascular abnormalities tend to have a signal intensity similar to or higher than that of muscle, are hyperintense on T2-weighted images, and enhance with contrast.

Developmental abnormalities

Developmental abnormalities affecting the head and neck region are numerous and vary in their presentation; a description of these conditions is beyond the scope of this chapter. However, MRI is beginning to be used in their assessment.

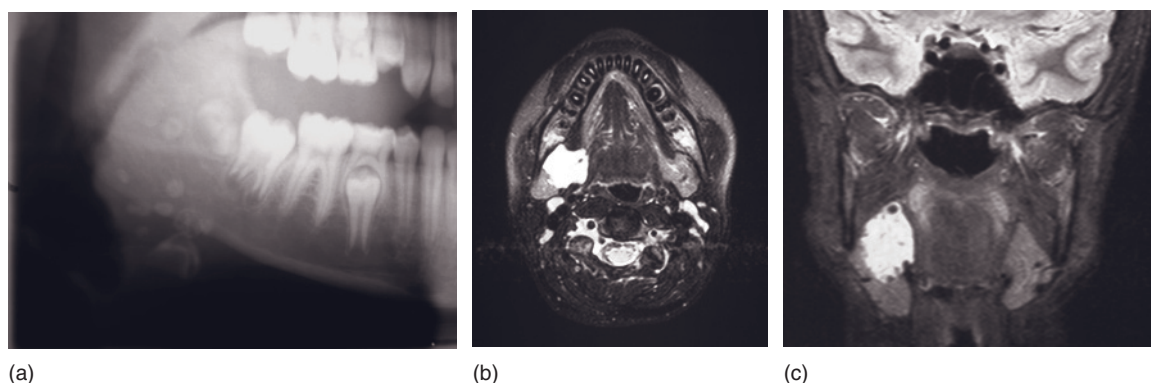


Figure 3.40 (a) Part of a panoramic radiograph showing several circular radio-opacities produced by phleboliths. Axial (b) and coronal (c) magnetic resonance imaging scans of the same patient showing a high signal lesion lying between the medial pterygoid muscle and the submandibular salivary gland. The signal voids are produced by the phleboliths.

One of the most common facial abnormalities is cleft lip and palate, affecting approximately one in 700 (0.7%) live births.⁹⁷ Until the development of CT, plain radiographs, both intraoral and extraoral, were the main imaging used in diagnosis and assessment for orthodontic and surgical treatment planning. The introduction of and subsequent improvements in CT and 3D CT scanning have allowed an accurate evaluation of bony defects, bone thickness, and associated soft tissues changes to assist the surgeon with, for example, planning bone grafting, implant assessment, and soft tissue functional studies. MRI is beginning to be used either as an alternative or a supplement to CT scanning.

Ultrasound is widely employed to diagnose prenatal clefts, but it can be limited by shadowing from ossified bone.⁹⁸ To help overcome this problem, MRI is increasingly being used, particularly after the first few months of pregnancy, to supplement ultrasound for abnormalities that are difficult to assess on the latter. Scans are obtained in the sagittal, coronal, and axial planes to assess the frontal and nasal bones, hard palate, micrognathia, tongue position, airway, lips, orbits, and ocular development. It is also important to evaluate other coexistent abnormalities, not only in the head and neck region (e.g., vascular abnormalities), but also of the spine, heart, and other tissues.

Unilateral clefts show deviation of the nasal septum to the affected side. Bilateral, complete clefts show protrusion of the premaxillary segment, and the lateral incisor tooth buds are usually missing. The secondary palate should be assessed, as this is not well demonstrated on ultrasound.⁹⁷

Inflammatory disease and tumors

Although this subject is outside the remit of this chapter, it is important to be aware that MRI is used for the detection and demonstration of inflammatory conditions and tumors. For this reason, these conditions should be considered, albeit briefly.

Figure 3.41 shows inflammation of the masticator space following an infection subsequent to root canal therapy on a lower molar tooth. There is a high signal of the T2-weighted image, showing the involvement of the inflammatory process in both the bone of the mandible and in particular the adjacent tissue.

Malignant tumors have a higher water content than normal tissue and thus have a high signal on T2-weighted images. To distinguish high-signal tumors from fat, sequences such as STIR are used to

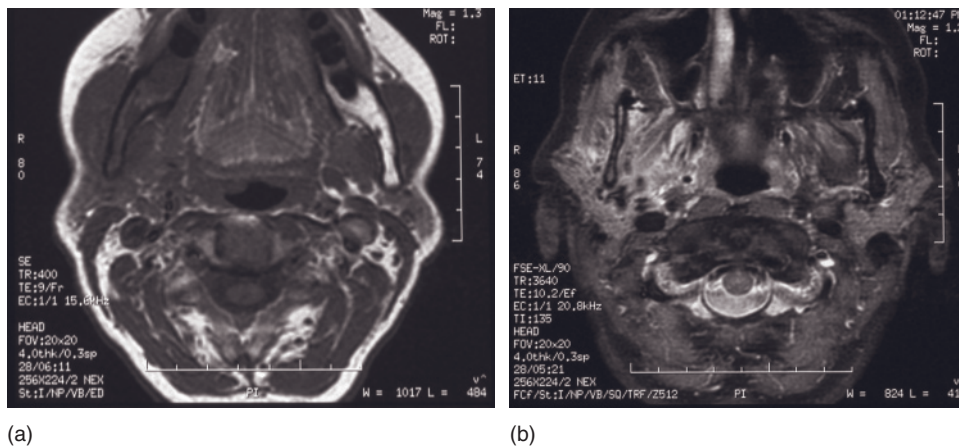


Figure 3.41 (a) A T1-weighted image showing low signal in bone in the right ramus, due to the presence of inflammation, compared with the high signal from the fatty marrow on the normal left side. (b) A T2-weighted image at a slightly higher level showing a high signal in the bone and surrounding soft tissues of the masticator space on the right side due to the presence of inflammation.

suppress tissue fat to make the tumor more obvious. Malignant tumors will usually enhance with gadolinium when it is given intravenously.

MRI is useful to assess patients with oral malignancies such as squamous cell carcinomas and may be used with CT or CT combined with positron emission tomography for occult lesions and lymph node assessment, such as in a lymphoma. It is used not only to identify the extent of the primary lesion, but also for local or distant metastatic spread. For example, MRI is used to show perineural spread as well as intracranial spread. MRI shows tumor margins well but may overestimate the size of a tumor in the presence of edema, as might occur if imaging takes place immediately after a biopsy.

MRI is superior to CT for imaging neoplasms of the salivary glands as the contrast between salivary gland tumors and normal glandular tissue can be poor. However, ultrasound should be considered as the initial investigation for a suspected salivary gland tumor as this imaging modality has a high sensitivity and specificity, particularly when combined with ultrasound-guided fine-needle aspiration biopsy. MRI, however, provides the surgeon with more easily understood graphic anatomic detail of a salivary mass and is necessary for the assessment of deep lobe parotid tumors, which do not show well on ultrasound. The most common tumor, the pleomorphic adenoma, has a low-to-intermediate signal on the T1-weighted image but a high signal on the T2 image (Figure 3.42).

CONCLUSION

Imaging forms an integral role in diagnosis and treatment planning in orthodontics and orthognathic surgery. In most cases, conventional imaging using a combination of periapical radiographs, occlusal radiographs, panoramic radiographs, and cephalometric radiographs is sufficient. However, in the more complicated cases, advanced imaging techniques such as CT, CBCT, and MRI may be required. These imaging modalities may be used to produce 3D images of the teeth and jaws. When soft tissue detail is

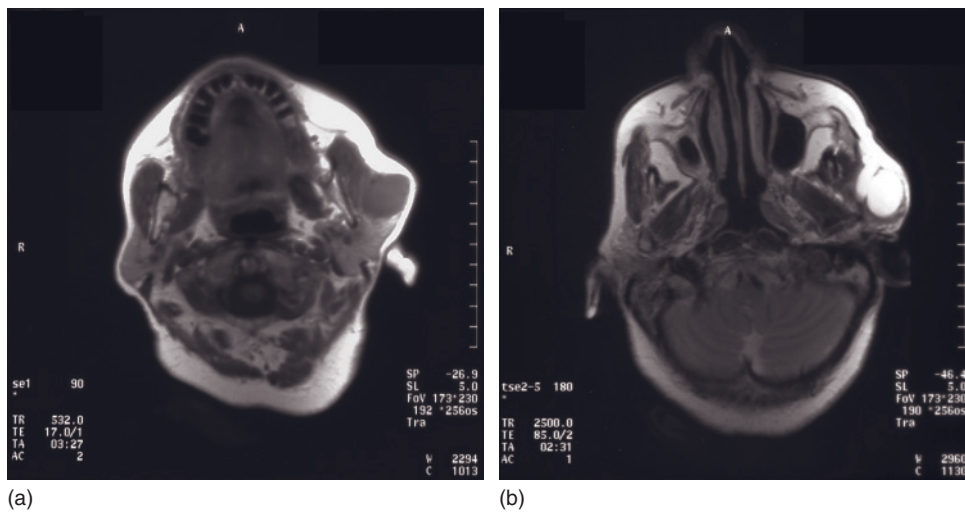


Figure 3.42 Magnetic resonance imaging scan of a patient with a superficial pleomorphic adenoma in the left parotid gland. On the T1-weighted image, the lesion has a low-to-intermediate signal (a), while on the T2 image, the lesion appears bright (b).

not required, CBCT may be used in preference to conventional CT as the radiation dose is generally lower. Although MRI shows excellent soft tissue contrast with no radiation dose, it requires further development with regard to 3D reconstruction and is not currently used routinely.

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4 Diagnostic Oral Pathology with Computed Tomography

Jerry E. Bouquot

INTRODUCTION

Among the most important aspects of patient care is the accurate diagnosis of the patient's disease. This task is made immeasurably more difficult by the fact that the clinical presentation of so many disease processes can be strikingly similar, despite potentially vast differences in etiology and pathogenesis. This is especially true for the many pathologic entities developing with the bones of the maxillofacial region.

Routine radiology has provided a reasonably effective means by which to distinguish one lesion or type of lesion from another, but the two-dimensional nature of radiographs imposes an obvious need for the interpretation of artifacts and superimpositions, making radiographic diagnosis more of an art than a true science. Nevertheless, the dental profession, or at least some among the profession, has been rather successful in formalizing an accurate system of radiographic features to aid in the development of a differential diagnosis of osseous lesions (Table 4.1).

The advent of the computed tomography (CT) scan greatly enhanced our ability to characterize pathologies of the maxillofacial bones, but the early images ("slices") were so thick and the distance between slices was so great, up to 7 mm, that much of the diagnostic detail was lacking and the clinician still had to extrapolate for an accurate interpretation. With more powerful computers and advanced programming allowing very small distances between slices and also allowing one to move smoothly through the slices for an almost three-dimensional view of a lesion, CT technology, including the cone beam CT (CBCT), has brought us to a level of unparalleled diagnostic capacity. In fact, these technologic advancements provide enough datapoints to actually allow the re-creation of the maxillofacial region in an undistorted three-dimensional image, including pathologic lesions (Figure 4.1).

This diagnostic advantage, however, is new enough that the dental profession has not yet had the time to establish a diagnostic classification system as useful as the one available for more routine dental

Table 4.1 Broad categories of radiographic characteristics used for differential diagnosis

Primary characteristic	Subcategories
Well-demarcated, unilocular radiolucency	Location: periapical, pericoronal, between roots, below inferior alveolar canal, etc.
Well-demarcated, multilocular radiolucency	Location: pericoronal, ramus, etc.; age at diagnosis
Poorly defined/moth-eaten radiolucency	Character of lesion periphery: poorly demarcated, ragged, moth-eaten, partial/irregular sclerosis
Multifocal or generalized radiolucency	Cortical expansion, symptomatic
Well-demarcated radiopacity	Evenly diffuse lesion, irregular opacities, encapsulation, sclerotic rimming, tooth-like structures, etc.
Poorly demarcated radio-opacity	Evenly diffuse lesion (e.g., ground-glass), irregular opacities, symptoms, cortical expansion, etc.
Multifocal or generalized radio-opacities	Location
Mixed radiolucent/radio-opaque lesions	Multifocal, generalized, cotton-wool appearance, onion skinning, peripheral demarcation, sclerotic rimming, tooth-like structures, etc.

Source: Modified from Neville *et al.*, 2008.

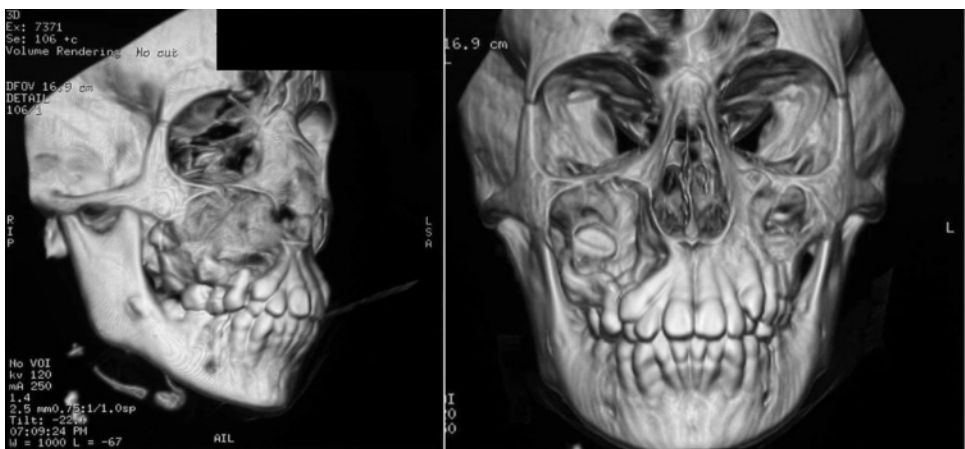


Figure 4.1 Three-dimensional rendering of cone beam computed tomography imaging data for a dentigerous cyst of the right posterior maxilla. Notice the tooth crown protruding into the cyst lumen.

radiographs. Only time will tell whether a new system will emerge or the old system will simply be refined, but it seems much more likely that the latter will occur.

ASSESSING THE LESIONAL BORDER

One of the major advantages of CT and CBCT imaging is its ability to better assess the margins or borders of an intraosseous lesion. This is extremely useful in determining the aggressive or infective nature of a pathologic entity. With routine radiology, a simple periapical cyst, for example, may be poorly demarcated when, in fact, it is found at surgery to have very sharp margins. This long ago led to the conclusion that one cannot radiographically distinguish between periapical cysts and periapical granulomas. With spiral CT or CBCT, considerable additional information can be derived relative to:

- the abruptness, or lack thereof, of the lesional interface with surrounding bone;
- the thickness of the reactive bone layer around the lesion (Figure 4.2);
- the uniformity of the reactive bone layer around the lesion;
- the attachment of the lesional tissue to surrounding bone versus complete isolation from surrounding bone (e.g., to distinguish between an osseous and an odontogenic lesion; Figure 4.3);



Figure 4.2 Comparison of a pantographic radiograph (top left) and computed tomography scan of a dentigerous cyst of the posterior right maxilla. Note the rather uniform, imperforated cortical expansion of this well-demarcated lesion.

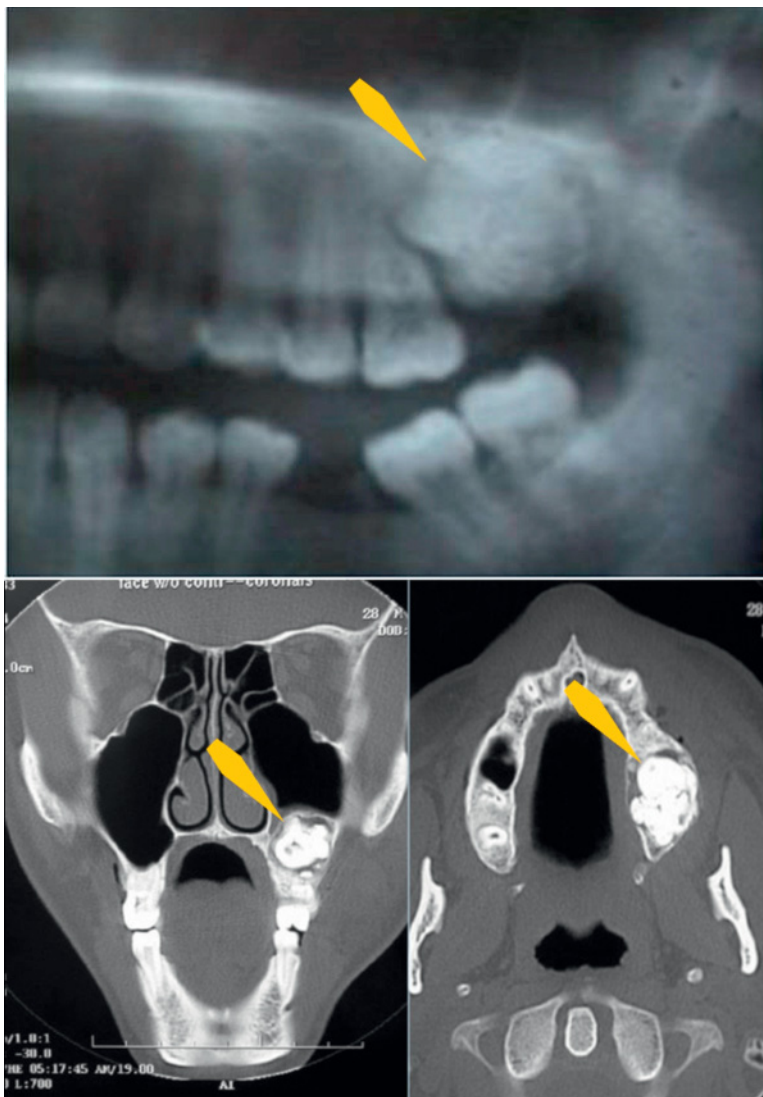


Figure 4.3 Comparison of pantographic radiograph (top) and computed tomography (bottom) images of a compound odontoma (arrows). Note the expansion into the sinus floor and the radiolucent fibrous capsule surrounding the lesion.

- areas of perforation of surrounding sclerotic rim or overlying cortex (Figure 4.4);
- erosion of adjacent osseous or dental structures;
- extension into the maxillary sinus (Figure 4.5).

Detailed assessment of the periphery is especially important because certain lesions will have a focus, perhaps only a small focus, of indistinct border or border perforation, possibly representing an area of infection, ischemic damage, or malignant transformation in an otherwise benign entity, which can

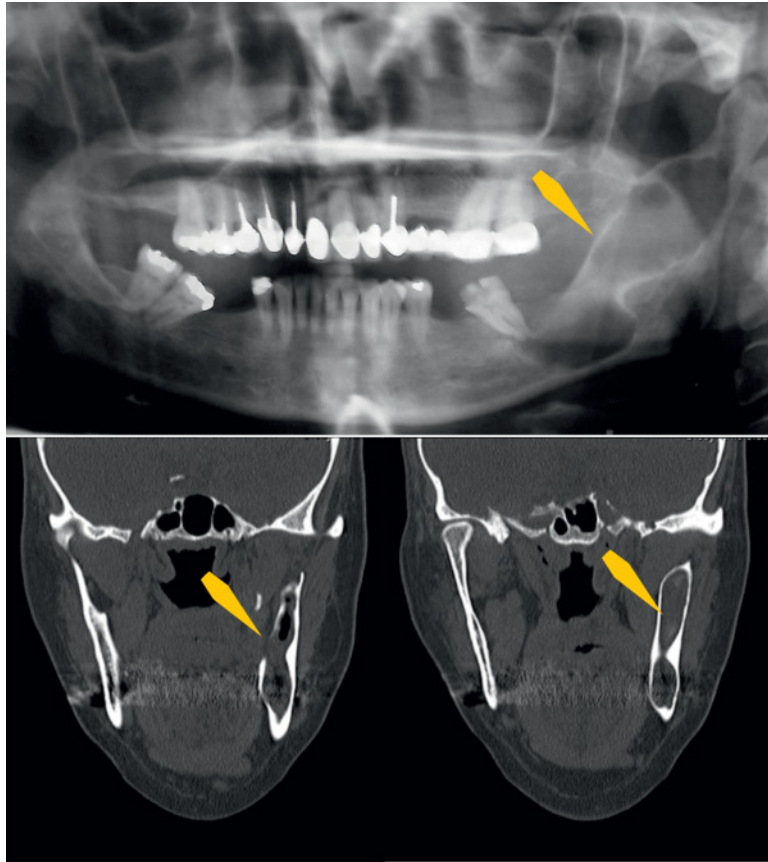


Figure 4.4 Comparison of pantographic radiograph (top) and computed tomography (bottom) images of an odontogenic keratocyst (arrows). Note the lack of cortical expansion and the lingual perforation.

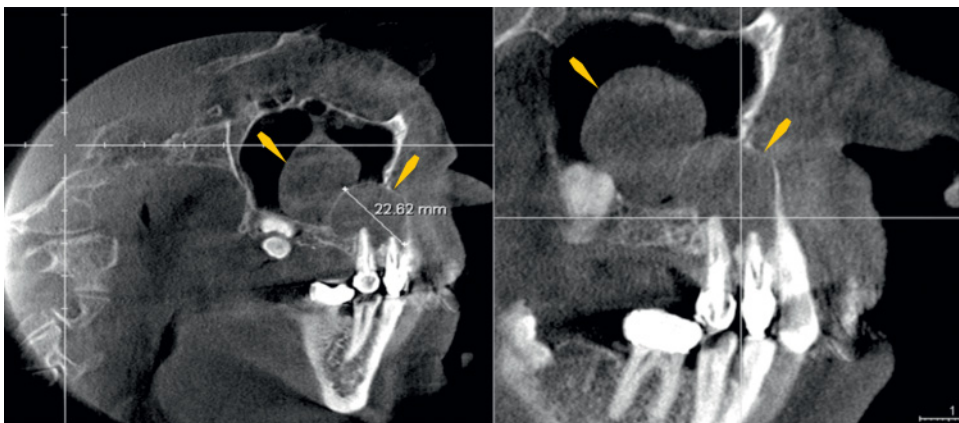


Figure 4.5 Cone beam computed tomography images of a periapical cyst expanded into the maxillary sinus (right arrows in each figure part), and a sinus "mucocoele" or pseudocyst of the lateral wall of the maxillary sinus (left arrows in each figure part).

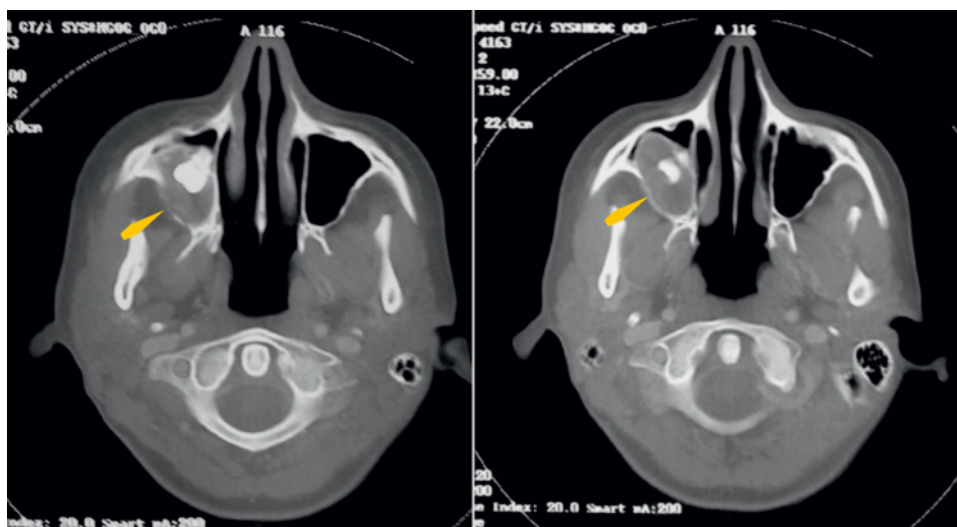


Figure 4.6 Computed tomography images of an impacted maxillary molar with an associated dentigerous cyst (biopsy showed it to be odontogenic keratocyst). Arrows point to posterior cyst wall with low bone density secondary to infection of the underlying cortical bone.

drastically change our understanding of the specific lesion. A cyst, for example, may develop infection and carcinoma (albeit a rare event), leading to a moth-eaten radiolucency, diminished bone density (Figure 4.6), or actual perforation (see Figure 4.4) of the thin bony wall surrounding it. Even a small area of inflammation or infection can explain a symptomatic cyst and may lead to an altered treatment plan or management, perhaps with preoperative antibiotics, or perhaps with extra attention paid to the area of interest during the surgery.

When the lesion is one that can perforate the overlying cortex and extend into surrounding soft tissues, such as an intraosseous malignancy, ameloblastoma (Figure 4.7), or odontogenic keratocyst (see Figure 4.4), the identification of a cortical defect becomes not only invaluable, but absolutely essential. Additionally, extension from the main body of an intraosseous lesion, such as is seen with a dental fistula, may be tracked with relative ease from the lesional origin to the end of the extension, for example a fistulous opening, with CT/CBCT imaging. These peripheral or border defects are seldom visualized with conventional dental radiology.

The well-demarcated border

A well-demarcated border, with a sharp, abrupt transition from lesion to surrounding bone, is, of course, a well-accepted sign of slow growth and a lesion, such as a cyst or benign neoplasm (see Figures 4.2, 4.4, and 4.7), that is pushing rather than invading into adjacent bone. The thin sclerotic rimming at the periphery of such lesions is the typical result of slow enlargement, representing the body's protective attempt to wall off the lesion, and this provides an additional assurance of the benign nature of the lesion. This concept was established via radiology, but modern CT and CBCT images allow an assessment of *all* margins, with no superimpositions, and especially allow an assessment of the uniformity of thickness of the reactive bony response (see Figure 4.2).



Figure 4.7 Comparison of pantographic radiograph (top) and cone beam computed tomography scan (bottom) of a large ameloblastoma of the left posterior mandible. Note the extensive cortical expansion with multiple small areas of cortical perforation on the computed tomography images.

Additionally, the complete *lack* of a bony reaction can provide good information. For example, a well-demarcated border without any bony reaction or sclerotic rimming should make one suspicious of:

- Langerhans cell histiocytosis (histiocytosis X);
- multiple myeloma;
- early Paget's disease of bone (osteoporosis circumscripta);
- a brown tumor in hyperparathyroidism.

The poorly demarcated border

When extensive or multiple radiolucencies have large regions with ill-defined or moth-eaten borders, the clinician's level of concern should be greatly increased: these are signs of infection or invasion. Since these changes are much more readily seen with CT/CBCT imaging, the new technology should naturally lead to an earlier detection of and intervention for aggressive entities, such as malignancy, with a subsequent improvement in prognosis; however, only time will tell whether or not this will become the case

as more and more dentists use CBCT scanning. This also, of course, lays an additional obligation on a dentist to look more completely and critically at lesional borders.

Poorly demarcated borders suggest, among other disease processes:

- infection (acute osteomyelitis, chronic nonsuppurative osteomyelitis, periapical granuloma, infected cyst);
- ischemia (osteonecrosis, bone marrow edema, neuralgia-inducing cavitation osteonecrosis, traumatic bone cyst);
- osteopenia (focal osteoporotic marrow defect);
- malignancy (osteosarcoma, fibrosarcoma, Ewing's sarcoma, reticulum cell sarcoma, metastatic carcinoma, malignant odontogenic tumors, primary lymphoma of bone, leukemia);
- massive osteolysis (i.e., vanishing bone disease);
- desmoplastic fibroma and fibromatosis of bone;
- odontogenic myxoma or myxofibrosarcoma.

Extension or invasion of a lesion beyond its borders is also a key indicator of aggressiveness, and this is often impossible to see without CT technology.

The changed cortex

CT/CBCT imaging allows a much more concise assessment of cortical changes or responses to a lesion when an intraosseous process has enlarged to the point of contact with the overlying cortex. A uniformly thin cortex is to be expected with benign, slowly expanding lesions (see Figures 4.2 and 4.6). Very thin cortices, however, are often so thin that they cannot be visualized with routine radiology; this is not the case with CT and CBCT images. The CT technology gives enough detail, moreover, to often allow a determination of whether the cortex has been broken from outside pressures (remember the “eggshell crackling” sounds) or truly perforated by the lesional tissues. Such perforation is, of course, much more likely to be seen in severe infection, necrosis, or malignancy when there is no attempt at expansion of the cortex.

A lack of cortical expansion, even without perforation, can provide important information. For example, one of the benign cysts of the jaws, the odontogenic keratocyst, shows a remarkable inability to expand the cortices laterally, even when it is huge in an anteroposterior dimension (see Figure 4.4). This characteristic of little or no facial or lingual expansion, then, provides a key point of diagnostic information that can rule out many, many other multilocular radiolucencies, yet the characteristic cannot be seen with routine dental radiographs.

Two odd maxillofacial lesions are quite difficult to assess radiographically but are extremely easy to see with CT/CBCT imaging, and in fact the diagnosis can be made using the CT or CBCT images exclusively. The first of these, the Stafne bone cyst/defect, presents as a lingual concavity of the posterior mandibular cortex. The concavity is easily seen on CT images, providing a definitive diagnosis without biopsy or further testing, but presents as an intraosseous lesion on routine radiographs.

The second lesion, the “mucocoele” or pseudocyst of the maxillary sinus, is a focal, sessile, edematous enlargement of the sinus lining, usually on the lateral wall of the maxillary sinus. This presents as a faint, diffuse, well-demarcated radio-opacity on pantographic radiographs and is extremely difficult to diagnose with just radiographs, yet a clinical diagnosis is important because no surgery or biopsy is required. With CT or CBCT imaging, the diffuse soft tissue enlargement and location become very easily identified

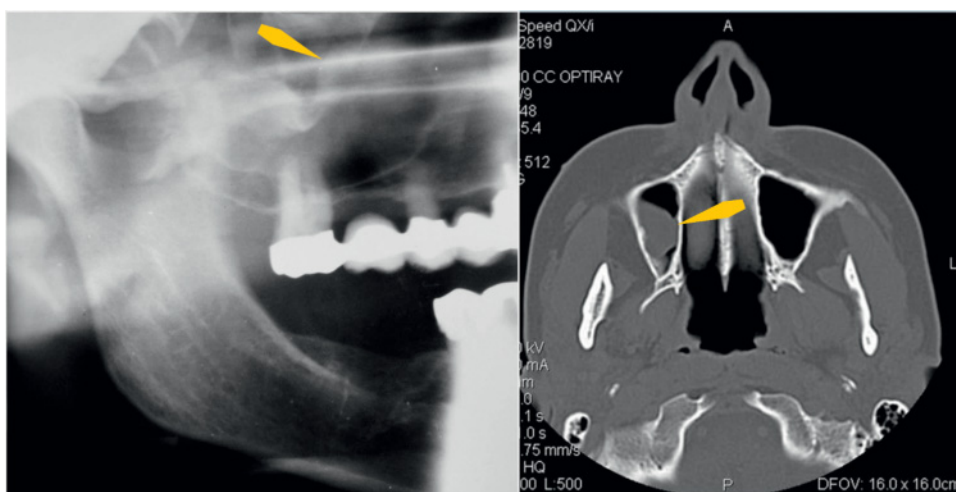


Figure 4.8 Comparison of pantographic radiograph (left) and cone beam computed tomography (right) images of a maxillary sinus “mucocoele” or pseudocyst of the lateral wall (arrows). The radiograph demonstrates a barely visible oval radiopacity, but the sessile, soft tissue nature of the lesion is readily visualized with cone beam computed tomography.

(Figure 4.8). Along this same line, variations in anatomic development are much more readily assessed with CT/CBCT images, especially the three-dimensional re-creations.

The poorly demarcated mixed lesion

Not all lesions with poorly demarcated borders are severe or aggressive. One of the more valuable uses of CT or CBCT scans is the more precise clarification of the variety of mixed radiolucent/radio-opaque lesions found in the jaws. This improvement in imaging will most likely lead to a new classification of such lesions and will allow the clinician to rather easily separate those entities that blend into surrounding bone, that is, actual bony lesions (Figure 4.9), from those with capsules, such as are found around the odontogenic tumors. This is of considerable diagnostic importance. For example, when a mixed lesion blends slowly into surrounding bone with no attempt at encapsulation, the differential diagnosis or list of likely diagnoses includes:

- bone dysplasias (fibrous dysplasia, Paget’s disease, early or mild osteopetrosis, focal osseous dysplasia, florid osseous dysplasia);
- benign bone neoplasms (osteoblastoma, enchondroma, internal osteoma, central ossifying fibroma);
- malignant bone neoplasm (osteosarcoma);
- reactive bone (condensing osteitis, idiopathic osteosclerosis, ischemic osteosclerosis, bone scar).

However, when a mixed lesion appears to be encapsulated, the following entities should be considered:

- odontogenic tumors (odontoma, Pindborg tumor, adenomatoid odontogenic tumor, ameloblastic fibro-odontoma, cementoblastoma);

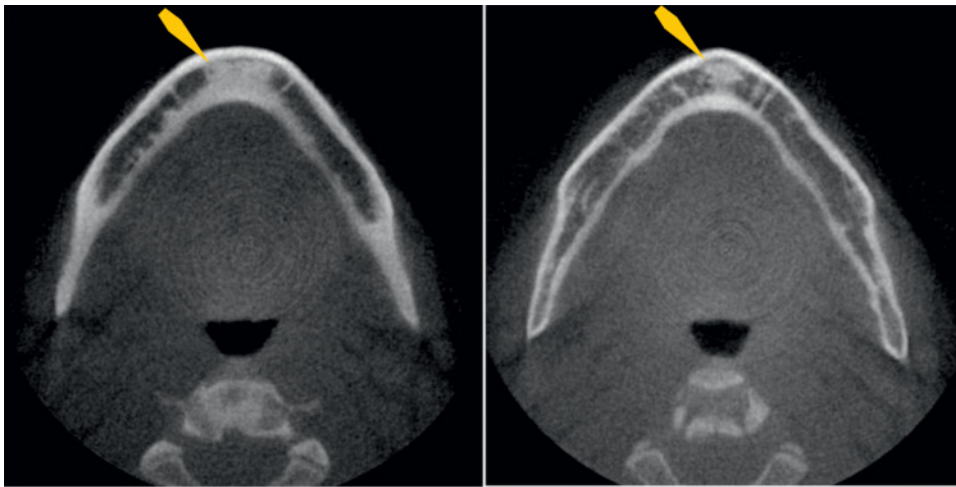


Figure 4.9 Computed tomography images of idiopathic osteosclerosis (arrows) show a lack of encapsulation and connection with overlying cortex.

- odontogenic cysts (Gorlin cyst);
- embedded root tip, partially resorbed impacted tooth, and supernumerary tooth.

CHARACTERIZING THE LESION

Without the superimpositions of two-dimensional radiographs, the characteristics of an intraosseous jaw lesion can be described much more accurately. The lack of sclerotic material in a radiolucency can be confidently confirmed, providing one differential diagnosis, or can be confidently *not* confirmed, that is, such material will be present, completely changing the differential diagnosis. These different lists were established with routine radiology, but the lack of superimpositions makes the assessment so much easier with CT or CBCT scans. Additionally, a scan can determine whether or not the radio-opacities are part of the lesion itself, that is, are scattered throughout the lesion, are centrally located within it (Figure 4.10), or are merely reactive bone at the periphery of the lesion, as is so commonly found in the central giant cell granuloma.

The CT or CBCT scan also makes the characterization of focal osteosclerotic regions more accurate. Without having to interpret superimposed calcified materials, it is much easier to say, for example, that a lesion has snowflake opacities (Pindborg tumor, Gorlin cyst, adenomatoid odontogenic tumor), cotton-wool opacities (Paget's disease, fibrous dysplasia, cemento-osseous dysplasias, ossifying fibroma, early osteopetrosis), globular opacities (cemento-osseous fibroma, complex odontoma), tooth-like shapes (odontoma, ameloblastic fibro-odontoma), or diffuse/ground-glass opacification (fibrous dysplasia, hyperparathyroidism). Also, the consistency of cortical masses, such as tori and exostoses, can be determined with accuracy. A torus composed entirely of marrow spaces, for example, might be at higher risk for bisphosphonate-associated osteonecrosis when a chronic surface ulcer is present.

Specific changes that are unique to certain rare diseases are also much more readily seen with CT/CBCT, such as:

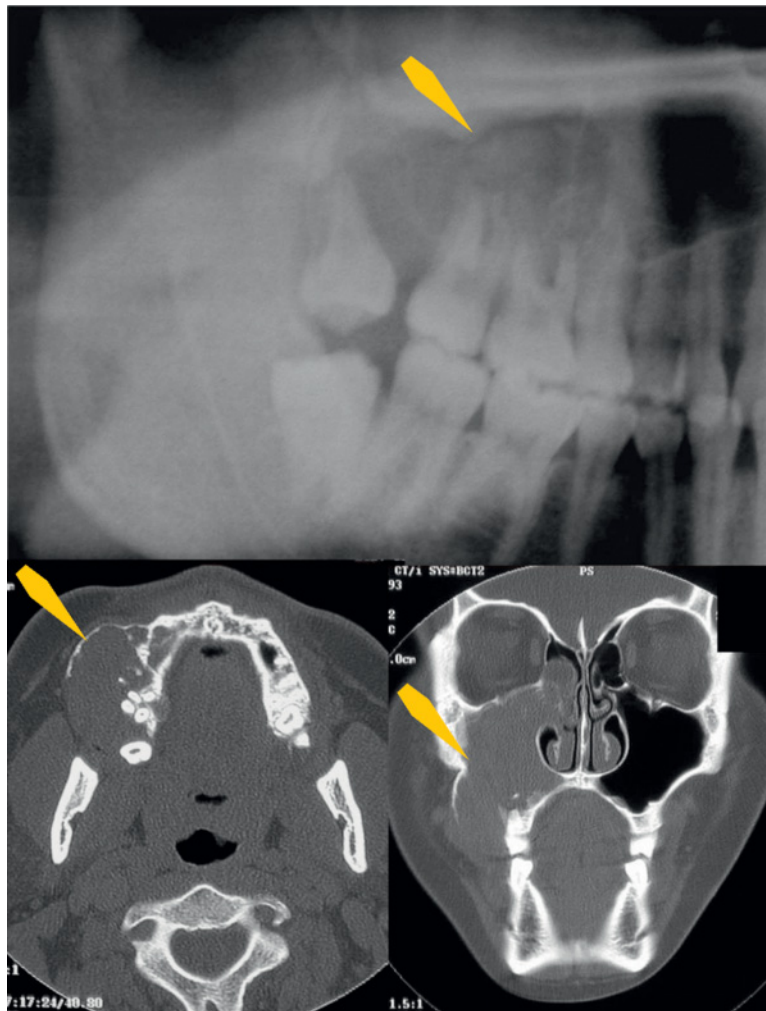


Figure 4.10 Comparison of pantographic radiograph (top) and computed tomography (bottom) images of a Pindborg tumor (arrows). Note the small radiopaque flecks on the left computed tomography image, indicative of calcification within the tumor itself. The cortex shows extensive destruction and expansion, with complete fill of the right maxillary sinus.

- an external sunburst pattern (osteosarcoma, fibrosarcoma, chondrosarcoma);
- an internal sunburst pattern (hemangioma);
- a peripheral onion-skin pattern (Garre's osteomyelitis, Ewing's sarcoma);
- loss of the lamina dura (hyperparathyroidism);
- fusion of bone with teeth (ankylosis);
- the honeycomb pattern of chronic ischemic bone disease;
- residual sockets (hormonal deficiency, hypocalcemia, chronic ischemia).

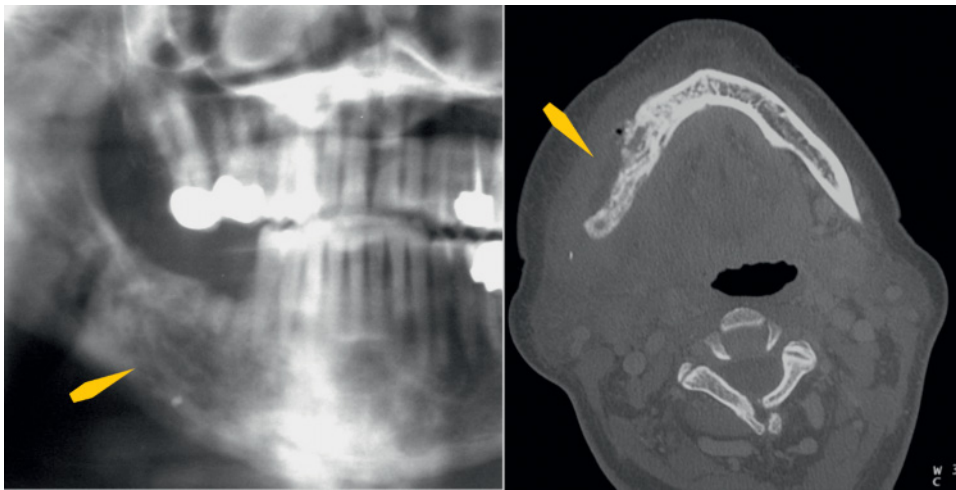


Figure 4.11 Comparison of pantographic radiograph (left) and computed tomography (right) images of chronic nonsuppurative osteomyelitis of the posterior right mandible, on the facial surface (arrows). Note the great destruction of the cortex overlying the area of involvement. The irregular, moth-eaten destruction hinted at on the radiograph is much more obvious on the scan.

DETERMINING THE LOCATION OF THE LESION

The CT/CBCT scan allows the clinician to exactly locate an oral pathologic lesion in relation to the teeth, the cortex, the alveolar nerves, and the maxillary sinus. This may greatly influence the surgical approach to such lesions. Although estimates of location can be determined with multiple views in routine radiology, the CT and CBCT technologies bring a completely new level of accuracy to this process. The clinician can now determine whether or not a mandibular molar's roots are wrapped around the inferior alveolar canal, an impacted tooth is very close to an erupted tooth, a tumor is very close to the mental foramen, a cyst of the anterior maxillary midline is within or outside the nasopalatine duct, and so on. This is such an important improvement that some consider the CT/CBCT scan to be *essential* to the proper workup of such lesions.

The localization of a lesion is especially important for moth-eaten or irregular radiolucencies, since malignancy or infection are almost always the underlying diagnosis. Radiographs are especially difficult to interpret for these entities, but CT or CBCT will show exactly where the disease is and how irregular the "invading" margin is (Figure 4.11). Scans are, moreover, excellent for determining the extent of bony destruction produced by an individual malignancy or necrotizing process (Figures 4.12 and 4.13).

MARROW DISORDERS

The CT/CBCT technology has added an entirely new ability to evaluate stromal marrow and marrow disorders of the jaws. Low bone density, as seen in osteoporosis, chronic ischemic bone

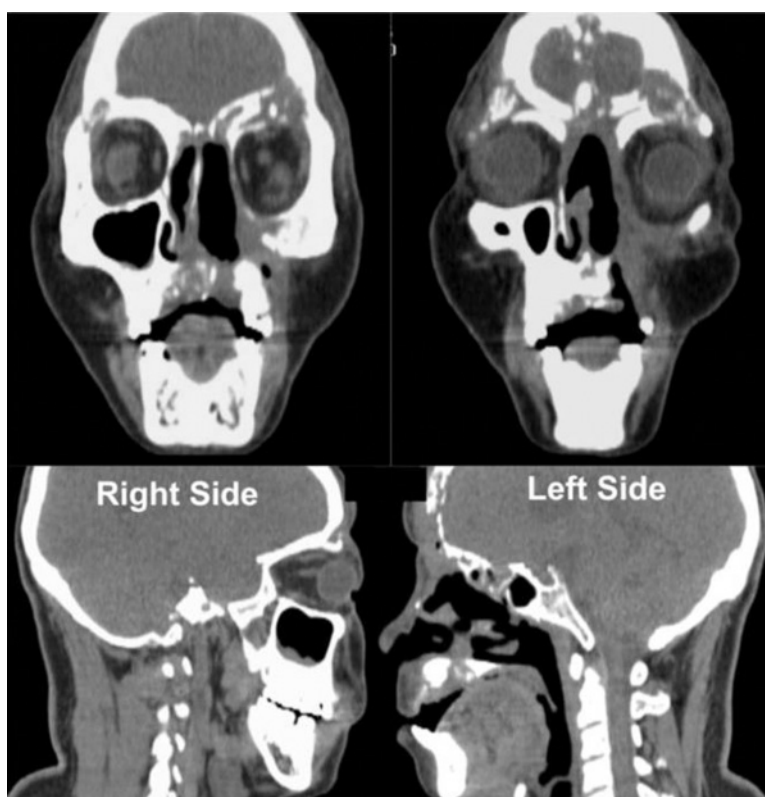


Figure 4.12 Two-dimensional computed tomography images of massive destruction of the bony structures of the left midface, extending into the frontal sinus region, in a patient with angiocentric B-cell lymphoma (midline lethal granuloma). (From Johnson *et al.*, 2007.)

disease, leukemic proliferation, and infiltrating disorders such as Gaucher's disease, is more readily assessed, as are pain-producing disorders, such as bone marrow edema and regional ischemic osteoporosis.

The intramedullary cavitations of traumatic bone cyst and chronic ischemic bone disease produce a very dark, black background, as opposed to the slightly hazy gray of the typical marrow-filled medullary spaces. This same intense darkness seen between thin but intact trabecula is characteristic of honeycomb bone, which appears at surgery to be similar to the dried jawbones used for student teaching and research, except that it is moist instead of dry. Both forms of bone have a complete lack of marrow within intramedullary spaces but radiographs cannot possibly identify this.

The broken, thin, misplaced trabecula and "calcific necrotic marrow detritus" of chronic ischemic bone disease can mimic a very faint variant of ground-glass bone, sometimes referred to as "ghost marrow" on radiographs; it is much more readily visualized with CT or CBCT imaging. The presence of a dense fibrous scar tissue over the top of a residual or intact socket years after the extraction is another feature of ischemic bone disorder that can be easily visualized by CT/CBCT but not by conventional radiographs.

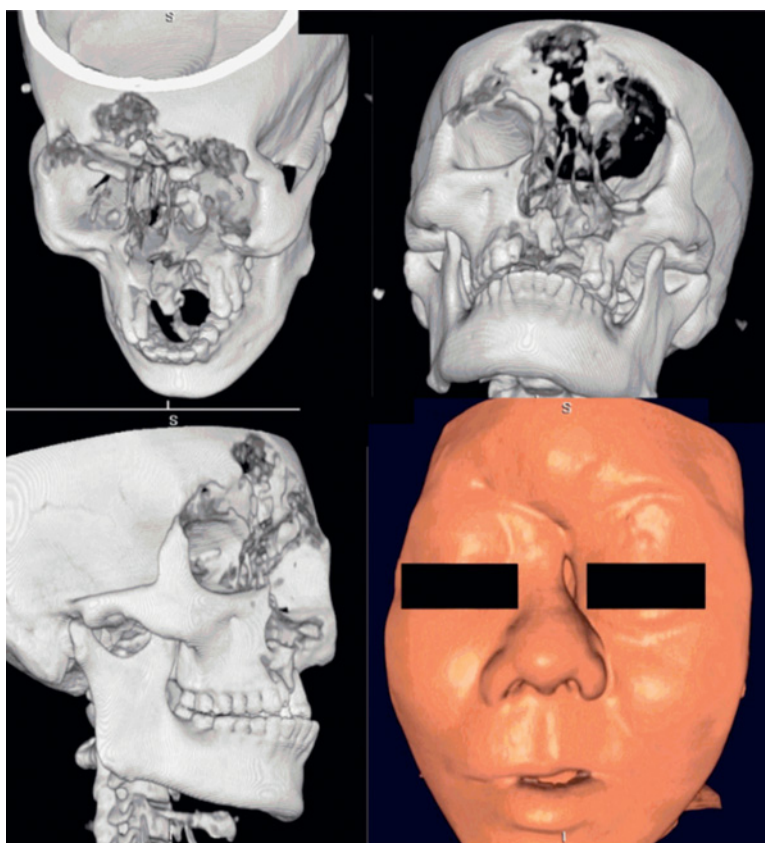


Figure 4.13 Three-dimensional computed tomography renderings of the same patient as in Figure 4.12 make the destruction of the maxillofacial and frontal regions more obvious. (From Johnson *et al.*, 2007.)

Maxillary sinus disease

The introduction of the pantograph more than 40 years ago gave dentistry a much better means by which to evaluate at least some of the disorders affecting the maxillary sinus. With CBCT imaging becoming more and more popular, and with so much more sinus data provided, the diagnosis of sinus lesions may soon enter into the realm of “routine” dentistry.

Areas of sinus membrane thickening, polypoid lesions, inflammatory and neoplastic masses, and cortical perforation or destruction (perhaps from dental infection) are routinely identified (see Figures 4.5, 4.8, and 4.10). The CBCT even allows the clinician to identify a central “ball” of aspergillois, which has a tendency to develop in the sinus when zinc-containing endodontic material is extruded into the sinus. Also, the “mucocoele” (pseudocyst) of the maxillary sinus can be diagnosed exclusively with CBCT (see Figure 4.8), when there is a broad, sessile base to a uniformly diffuse soft tissue bulge on the lateral wall of the sinus; this could only be suggested with conventional radiology.

The nearness of a root tip to the sinus can be easily determined using CT or CBCT imaging, and may alter the treatment plan for an extraction, or the fact that the root tip is *already* in the sinus prior to extrac-

tion will allow the clinician to warn the patient that a sinus perforation is unavoidable. Along this same line, the spatial association between a localized sinus membrane thickening and a tooth apex can suggest that a patient's chronic sinusitis might be related to dental infection rather than seasonal allergies. Additionally, a root tip that fractures off during extraction and falls into the sinus can be much more readily found and localized compared with conventional radiographic techniques.

FOLLOW-UP

One of the most valuable of all of the features of the CBCT scan is the ability to compare, without spatial distortion, bone changes before and after treatment. Complete removal of an intraosseous lesion, even an impacted tooth, is much more accurately assessed than with routine radiology. Lesions that have been deemed to be innocuous or "burned out," such as a central cementifying or ossifying fibroma in an older individual, and fibrous dysplasia or cherubism in an adult, can be accurately measured to see whether or not there is any change over time. Additionally, increased calcification, which is a common feature of mixed lesions even after they have finished expanding, can be much more accurately assessed, even measured. Recurrences of removed bony lesions can be found at a much smaller size than with conventional radiology, and the exact location can be determined, perhaps allowing for more conservative removal.

CONCLUSION

There is no doubt that, within a short time, the CBCT has become a diagnostic tool of choice for the workup of oral pathologic entities within the maxillofacial bones, more so than the routine CT scan, which has been available for many decades. Improved techniques and diagnostic expertise will surely lead to a refinement or re-creation of our present lists of differential diagnoses, upon which, in turn, our management or treatment plans are based. This can only be good for dentistry and dental patients alike.

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5

Three-Dimensional Diagnosis and Treatment Planning of Dentoalveolar Problems

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INTRODUCTION

Dentoalveolar surgery is often required for the removal of impacted teeth, difficult extractions, the exposure of teeth for orthodontic reasons, and endodontic and implant surgery. Diseases of the jawbone and soft tissue are also treated in this field of oral surgery.

X-ray imaging is frequently applied to support the clinical diagnosis of dentoalveolar problems and to establish a treatment plan. For the broad scope of interventions in dentoalveolar surgery, a range of different imaging procedures and technologies are available. The basic diagnostic tools are two-dimensional (2D) radiographs such as panoramic, periapical, cephalogram, and transversal images. In the early 1970s, the 2D spectrum of diagnostic capabilities was extended by three-dimensional (3D) imaging based on computed tomography (CT).¹ Since then, the high-paced development of 3D imaging in dentistry has led not only to an excellent image quality, but also to a wide range of software applications supporting diagnosis and treatment planning in dentoalveolar surgery. These include:

- 3D representations of tomographic scans that can be reconstructed and visualized from arbitrary views by computers;²
- virtual as well as real stereolithographic 3D models that can be generated individually for each patient and used as models for exact surgical planning and the prediction of surgical outcomes;³⁻⁵
- computer-driven, image-guided robots that can be used to precisely and constantly drill, cut, and saw;⁶
- virtual surgical training devices and 3D representations of normal anatomy that may be used to enhance medical education and training;⁷
- tomographic scans and 3D models that can be matched to the real operating scene and provide the surgeon with image guidance during surgery.^{6,8,9}

Although these technologies were in part developed in other fields of oral and maxillofacial surgery, dentoalveolar surgery has greatly benefited from these developments, especially in the field of dental implantology. Computer-aided planning software based on 3D imaging has been established since the late 1990s.¹⁰ Following this development, different approaches to transfer virtual plans into surgical reality have been proposed and clinically applied.

The aim of this chapter is to introduce the diagnostic options and capabilities of 3D imaging in combination with computer-aided methods for the treatment of dentoalveolar problems.

Requirements for 3D imaging in dentoalveolar surgery

For a successful application of 3D imaging over the wide spectrum of dentoalveolar problems, a sufficient volume size, the highest possible spatial resolution at short exposure time, and the lowest possible dose are required. Furthermore, the space requirement for the unit should be small, and the operation and positioning of the patient efficient and simple, so that imaging can be well integrated into the clinical workflow.

The required volume size depends upon the relevant indication but should as a rule display the area of interest with a sufficient safety margin. For osteotomies of wisdom teeth, present in all quadrants, and for implant planning, both jaws should be shown completely, as well as the temporomandibular joint for implantologic diagnostics and planning. For other impacted or retained teeth, a smaller volume may be sufficient, but for smaller volumes (e.g., $6 \times 6 \times 6$ cm), positioning of the patient is critical since the volume of interest has to be aimed at before the exposure. Volumes too small in size tend to provoke repetitive scans since the volume of interest is not fully contained in the actual scan, resulting in an additional dose for the patient.

The spatial resolution should be between 0.3 and 0.8 mm for displaying dental structures.¹¹ However, for a proper diagnostic workup of impacted teeth and endodontic surgery, a resolution of 0.1 mm or less is desirable in order to diagnose subtle pathologic processes involving the root canals or the periodontal ligament.

Image quality and resolution are influenced by the amount of dose applied, the duration of the scan (i.e., probability of motion artifacts), and the reconstruction algorithms. The shortest possible exposure time is crucial, since the risk for moving artifacts rises with longer exposure times.¹² The necessary dose for 3D imaging for planning dental implants should be comparable to that of conventional exposures, whereby the exposures for the conventional second-plane X-ray must be considered in the total summation. The exposure itself should be able to display clearly in 3D the bone substance of the region of interest, and permit comparative density measurements for estimating the bone quality.

Requirements for 3D diagnostic software

With the advent of 3D image volumes, a significant amount of additional information is available to the dentist. Considering an efficient clinical workflow, the software for inspecting 3D image volumes has to be designed specifically for its main group of users, and thus prioritize dental requirements over radiologic ones. For 3D diagnostics in general medicine, predominantly orthogonal slice views are used, and doctors are trained accordingly. In dentistry, panoramic, periapical, and occlusal radiographs and cephalograms are common radiologic techniques. Slice-based diagnostics have so far been rarely used in dentistry and are therefore challenging for many active practitioners.

To provide the user with a familiar environment, some software mathematically calculates a panoramic view from the 3D data record as an overview. For a dentist, this means that a customary clear

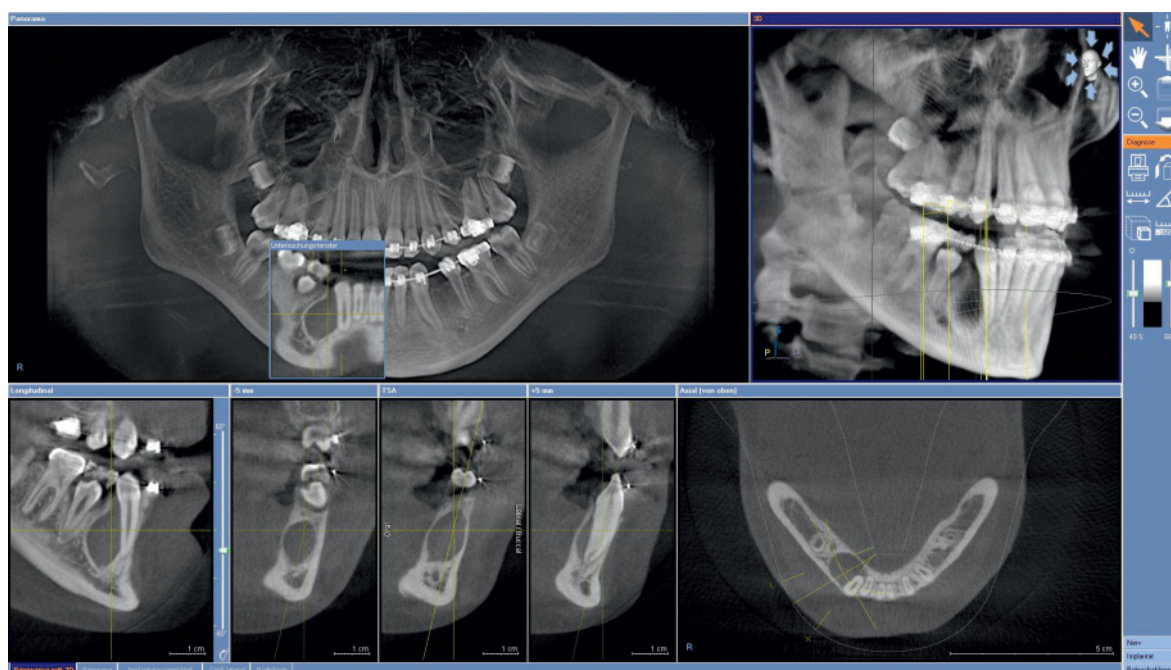


Figure 5.1 User interface of the GALILEOS System (Sirona Dental Systems, Bensheim, Germany), offering a panoramic and volumetric view in the upper row for overview as well as perpendicular cuts in the lower row, providing a clear visualization of the anatomy.

display of the relevant anatomy should be easy as a navigational basis in the 3D space (Figure 5.1). Using that functionality requirement, the common panoramic view can be linked to the 3D information provided by the scan. This approach cannot only be realized for the panoramic view, but also for cephalograms. Basic functionality as measuring true distances and angles, as well as contrast and brightness adjustment, are mandatory in 3D software packages.¹³

CLINICAL APPLICATIONS

In the following section, clinical examples ranging from impacted teeth to implant cases are given for the application of 3D diagnostics and treatment planning based on cone beam imaging.

TREATMENT PLANNING FOR RETAINED OR IMPACTED TEETH

The surgical removal of retained or impacted teeth is one of the most common procedures in dentoalveolar surgery.¹⁴ One of the primary causes of this disturbance in eruption is a lack of space. The third molars, which erupt last, are affected most frequently.¹⁵ Depending on the horizontal growth of the jaw, the available space may be inadequate for the molars erupting last in the dental arch, resulting in impacted and/or ectopic wisdom teeth in the region of the mandibular angle.

Besides the wisdom teeth, the maxillary cuspids exhibit the highest incidence of eruption disturbances. These are usually caused by an early loss of the deciduous teeth with mesialization of the premolars erupting before the cuspids. In addition to genetic factors, exogenous influences also determine the eruption of the permanent teeth, resulting in impaction caused by trauma, apical periodontal pathologies, and cyst formation.¹⁶ In many cases, the etiology of eruption disturbances remains unknown.

With the exception of the wisdom teeth, the diagnosis of impacted or ectopic teeth is frequently incidental because they are often clinically asymptomatic and are rarely accompanied by other pathologic processes.¹⁷ Besides the wisdom teeth, the maxillary and mandibular second molars and the maxillary cuspids are most frequently displaced.¹⁸ If the clinical examination records a delayed eruption, dental migration, or an alteration in the bony structures such as a prominence, an X-ray image should be prepared. The affected groups of teeth are described in the following section.

Ectopic incisors

Ectopic incisors are associated with supernumerary tooth buds in the anterior maxillary region and can also result from trauma to the deciduous dentition. 3D imaging allows the exact localization of the tooth and the identification of its root length and root path. Ectopic front teeth frequently exhibit a bend in the root, that is, a dilaceration that can complicate the classification of the tooth.¹⁷

Ectopic maxillary cuspids

Ectopic cuspids occur in 1–3% of cases, making them less common than ectopic wisdom teeth.¹⁵ Palatal displacement is 2.5–5 times more common than buccal displacement. A close topographic relationship with the adjacent teeth often exists, and the root may deviate from the longitudinal axis. A radiologic diagnosis of these clinically concealed teeth provides information on their location and morphology, as well as on adjacent structures.¹⁹ This includes their positioning and angulation in the dental arch, their developmental stage, the shape and length of the root, the size of the follicle, and possible resorptions on adjacent teeth.

2D images are of limited use. The 3D image of ectopic cuspids permits their differentiated examination and serves as a valuable diagnostic tool. In contrast to conventional 2D imaging, the teeth can be more accurately localized, the possibility of orthodontic correction of the tooth can be assessed based on the periodontal gap, and damage to adjacent structures can be evaluated using a 3D image.

Ectopic mandibular cuspids

The less common displacement of the mandibular cuspids can extend to the mandibular border. The transverse orientation of the tooth and its position in the bone structure should be determined prior to treatment. If a tooth is located in the compact cortex, it must first be moved towards the spongiosa, facilitating orthodontic correction.

Ectopic premolars

Ectopic premolars frequently occur at the end of the primary dental lamina. They can be associated with supernumerary teeth. Due to their location at the transition of the dental lamina, displacements may range from mild manifestations to inversions of the tooth germ.

Ectopic molars

With the exception of the wisdom teeth, ectopic molars are rare and are associated with ectopic adjacent tooth germs.

Imaging parameters

In all eruption disturbances, the decision to either remove, leave, or orthodontically integrate the tooth has to be made by the treating dentist. Together with the clinical history, the diagnostic X-ray procedure is the foundation for this important therapeutic decision (Figure 5.2). The following questions should be answered from the diagnostic X-ray for impacted teeth in order to formulate an appropriate treatment plan:

- What are the dimensions of the tooth, and is there enough space for eruption and integration into the dentition?
- What is the distance to the occlusal plane?
- Is the tooth ankylosed?
- What is the surrounding bone structure of the tooth?
- Are neighboring teeth resorbed, or can a resorption be expected?

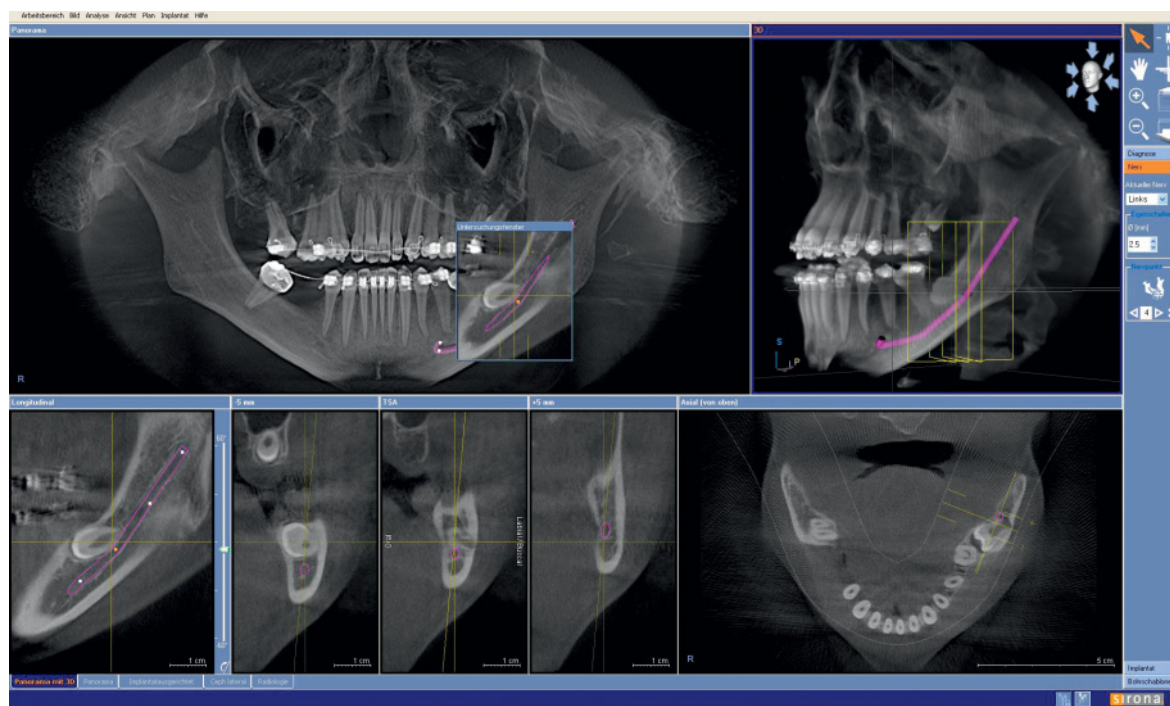


Figure 5.2 Visualization of an impacted third molar in the lower left jaw. The canalis mandibularis is marked.

- Can a cystic process be detected?
- Is the tooth malformed?

In the case of leaving the tooth in its position, the patient has to be informed about the potential risk of developing complications and has to be advised for recall. If the tooth can be integrated into the dentition by orthodontic treatment, a surgical treatment plan has to be established to intraoperatively apply a bracket to the tooth that can be used to pull the tooth into occlusion.

The indication for surgical removal of the impacted or retained tooth should be formulated either if integration into the dentition is unlikely to be achieved or if any negative consequences for the surrounding anatomic structures are present or can be expected, as for example the development of a cystic lesion, recurring inflammation (pericoronitis) or the resorption of neighboring teeth.

ORTHODONTIC INTEGRATION OF IMPACTED OR RETAINED TEETH

In order to integrate teeth by orthodontic treatment, the position and angulation of the tooth and its surrounding structures and their relation to the tooth to be integrated have to be clearly identified. Depending on the buccal or oral position, the age of the patient, and the distance of the tooth to the occlusal plane, a combined orthodontic–surgical treatment plan is established. The pre-treatment radiologic information can be used not only to optimally prepare the surgical intervention, but also to estimate the following orthodontic treatment duration.²⁰

SURGICAL REMOVAL OF IMPACTED OR RETAINED TEETH

For any tooth removal, intimate anatomic relationships to the normal structures exist, so that accurate diagnostics are required to prevent secondary injury when removing persisting teeth in abnormal physiological positions.²¹ Therefore, several diagnostic questions arise prior to surgical removal that can be resolved by 3D diagnostics:

- The anatomic relation to:²²
 - the alveolar nerve
 - the adjacent teeth
 - the maxillary sinus
 - the nasal floor and cavity.
- The surgical approach:
 - a vestibular or oral surgical path
 - sectioning of teeth if necessary
 - the size of the osteotomy.

The risk of surgical complications involving the surrounding anatomic structures can be reduced by 3D preoperative imaging.²² When planning the surgical procedure, detailed 3D information about the spatial relationship of the tooth to be removed to its surrounding tissues permits not only a clear visualization, but also exact measurements. By assessing the space between the structures involved, minimally invasive surgical approaches can be chosen. This is especially so in the adolescent patient and allows for

minor soft tissue preparation and a precisely described surgical procedure. Particularly in dental malformations with associated impaction, preoperative diagnostics allow an estimation of the ability to preserve the tooth and a determination of further therapeutic procedures.²³

For wisdom teeth, space limitations often cause eruption disturbances with symptoms ranging from severe pain to recurrent inflammatory reactions in the context of pericoronitis. In addition to the determination of the anatomic position of the tooth, the 3D image serves in the evaluation of crown and root structure and of root growth.²²

The 3D image is particularly useful in evaluating potential damage to adjacent structures. For that purpose, specific software tools have been developed that enable the user to enhance the path of the mandibular canal, facilitating the preoperative assessment of its anatomic relation to the tooth to be removed.

From a surgical point of view, ectopic or impacted wisdom teeth are preferably removed after root growth has been substantially reached, ensuring better positional stability of the tooth in the surgical field than would be the case with germectomy. The risk of nerve damage increases significantly with age. Age 25 is given as the critical age. Especially in cases where the root is close to the nerve canal, 3D diagnostics provides greater diagnostic reliability than the combination of panoramic radiography and cranial posteroanterior survey imaging (occipitofrontal beam path, 15 degrees inclination with an open mouth).²⁴

With advanced age or in cases of pronounced displacement, cysts may form. As a rule, the impaction of wisdom teeth is less pronounced in the maxilla than in the mandible. To aid in the prevention of an oroantral fistula, 3D diagnostics provides accurate information regarding the position and characteristics of the roots and of the osseous boundary to the maxillary sinus. In the very rare cases of extreme displacement of wisdom teeth in the maxilla, 3D diagnostics permits an accurate positional determination and an assessment of cystic changes, and thus also determines whether extraction is indicated. By virtue of computer-assisted surgery, such teeth can be easily located, and tissue can be removed conservatively.

Summary

The various manifestations of eruption disturbance require an accurate determination of tooth position relative to the adjacent anatomic structures. 3D diagnostics permits an accurate determination of positional relationships and facilitates a prognosis regarding the course of continuing therapy. This eliminates the positional determination via the preparation of different single images, often with eccentrically guided beams or in several planes. These imaging combinations involve some uncertainty regarding the projection direction and rarely permit an accurate metric analysis or inform about the tissue structure for an assessment of bone quality or the width of the periodontal space.²⁴

In orthodontic treatment planning, the assessment of the position and degree of ankylosis of the impacted tooth, of bone quality, and of spatial relations permits a prognosis to be made for successful orthodontic adjustment. An accurate metric analysis facilitates a decision regarding the orthodontic correction of the teeth versus their surgical extraction. If surgical interventions are required, 3D imaging permits accurate surgical planning, and the patient can be informed visually regarding potential risks. For preoperative preparations, the extent of surgery can be determined based on the characteristics of the ankylosis, and the operative risk can be assessed. By virtue of accurate metric diagnostics, the surgery can be optimally prepared, and the surgical access can be planned to conserve tissue.²⁵

Depending on the degree of displacement, navigation-guided surgery can be used for a minimally invasive surgical approach. The resulting spatial orientation shortens the surgical time and reduces the degree of postoperative symptoms.²²

CYSTIC LESIONS

Cysts are defined as pathologic cavities filled with fluid, semi-fluid, or gaseous contents, and are frequently lined with epithelium. Most cysts grow slowly and expansively in size. This pathophysiological process is maintained by the osmotic gradient from the outside to the inside of the cyst. External fluid follows the osmotic gradient and enters the cyst, which increases the intracystic pressure, resulting in pressure-induced atrophy of the surrounding bone. As cysts remain clinically silent in the initial presentation, the radiologic diagnosis is often by chance from images indicated for other reasons. Since significant bone loss may occur before clinical signs arise, the early diagnosis of cysts can be extremely beneficial for the patient.

If clinical features are present, a bony hard lump with normal overlying mucosa, followed by compressible fluctuant swelling, can be observed. Discharge into the mouth and pain due to secondary infection are also typical signs of cysts. In addition, pathologic fractures due to the weakening of the bone, primarily the mandible, can cause symptoms such as occlusion disturbance, pain, and hypesthesia. To further differentiate the clinical finding, a vitality test and inspection, as well as palpation, of the area of interest are required.

The current World Health Organization classification of 2003 discriminates epithelial cysts into developmental odontogenic and non-odontogenic types, and apart from inflammation-associated cysts.⁶ Another group following that classification comprises aneurysmal and traumatic (pseudo-) cysts classified as non-neoplastic bone changes.⁶ Cysts caused by an inflammation (radicular cysts) are most common (56.9%). Follicular cysts (21.3%), keratocystic odontogenic tumors (keratocysts; 10.6%), and ameloblastomas (4.1%) are significantly less frequent.²⁶

The radiologic examination takes a central part within the diagnosis and surgical management of cysts. Characteristically, cysts present in the X-ray image as smoothly bordered, roundish, sometimes multi-chambered radiolucencies with radio-opaque margins, which can be absent when inflamed.¹⁴ Although the definite diagnosis of a cystic lesion is based on histologic examination, certain radiologic features help to establish a working diagnosis. By considering the patient history, localization, borders to adjacent structures, shape demarcation, expansion, and internal structure it is frequently possible to narrow down the differential diagnosis.

The initial diagnosis is frequently by chance and based on panoramic or intraoral X-ray images. For larger defects, further radiologic procedures that help to assess the extent of a lesion are required, especially when it lies close to affected structures such as the nasal floor, the maxillary sinus, or the inferior alveolar nerve.

The exact radiologic description of the lesion has therapeutic consequences: frequent treatment options are the cystectomy or cystostomy depending on the kind of lesion, patient compliance, the size of the lesion, and the involvement of neighboring structures. For pathologies that tend to recur, such as the keratocystic odontogenic tumor, it is vital to visualize the extent. Therefore, a 3D image modality is frequently required to establish a surgical treatment plan. Before the advent of cone beam imaging, CT or magnetic resonance imaging was frequently indicated. With increasing access and a better risk–benefit ratio, cone beam imaging appears as the modality of choice for the exact description of cystic lesions in the jaw (Figures 5.3–5.5).



Figure 5.3 Panoramic reconstruction from a three-dimensional scan indicated for implant planning in the lower right jaw. Teeth 21 and 24 show apical radiolucencies.

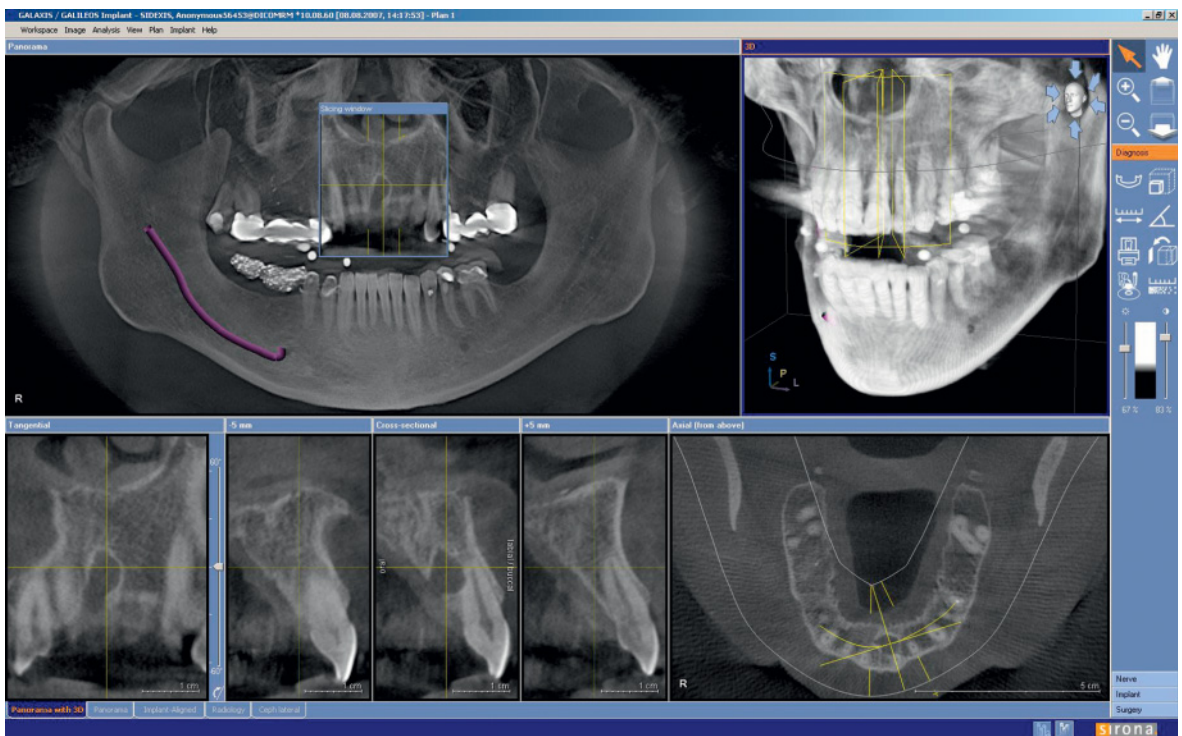


Figure 5.4 On closer three-dimensional inspection, the radiolucency on tooth 21 emerges as a nasopalatal cyst eroding the root of 21.

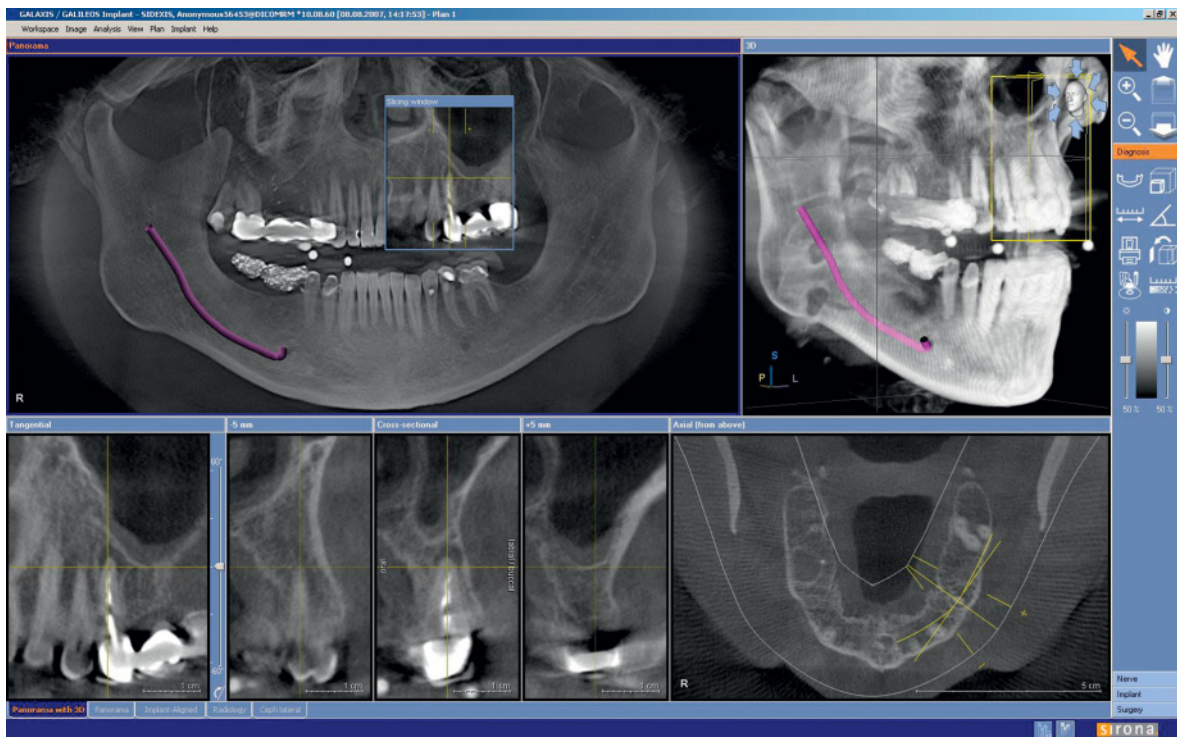


Figure 5.5 The radiolucency on tooth 24 emerges as an apical granuloma, probably caused by the insufficient endodontic treatment.

ENDODONTIC LESIONS

At present, endodontic treatment is characterized by modern treatment instruments and highly effective disinfection and filling materials. Failures are frequently caused by mechanical failure, debonding of the post, problems associated with the type of restoration, or periapical radiolucencies.²⁷ It has been reported that 50–75% of retrospectively observed endodontic fillings are judged inadequate. Either the filling is too long, too short, or not sufficiently condensed (Figure 5.6).

An exact understanding of the underlying anatomy is the foundation for a successful endodontic treatment. Cone beam imaging offers the possibility to visualize the anatomy in 3D, including accessory root canals insufficiently shown by conventional radiographs. It can also be advantageous for the early detection of periapical diseases and the exact measurement and characterization of periapical lesions. Root fractures, root canal anatomy, and the true nature of the alveolar bone topography around teeth may be assessed. For planning periapical surgery, cone beam scans can be successfully applied to determine the thickness of the vestibular cortical plate of, as well as the exact localization and inclination of, the roots in relation to the surrounding jaw. In addition, the topical relationship to the maxillary sinus or that of the inferior alveolar nerve to the root apices may also be clearly visualized.

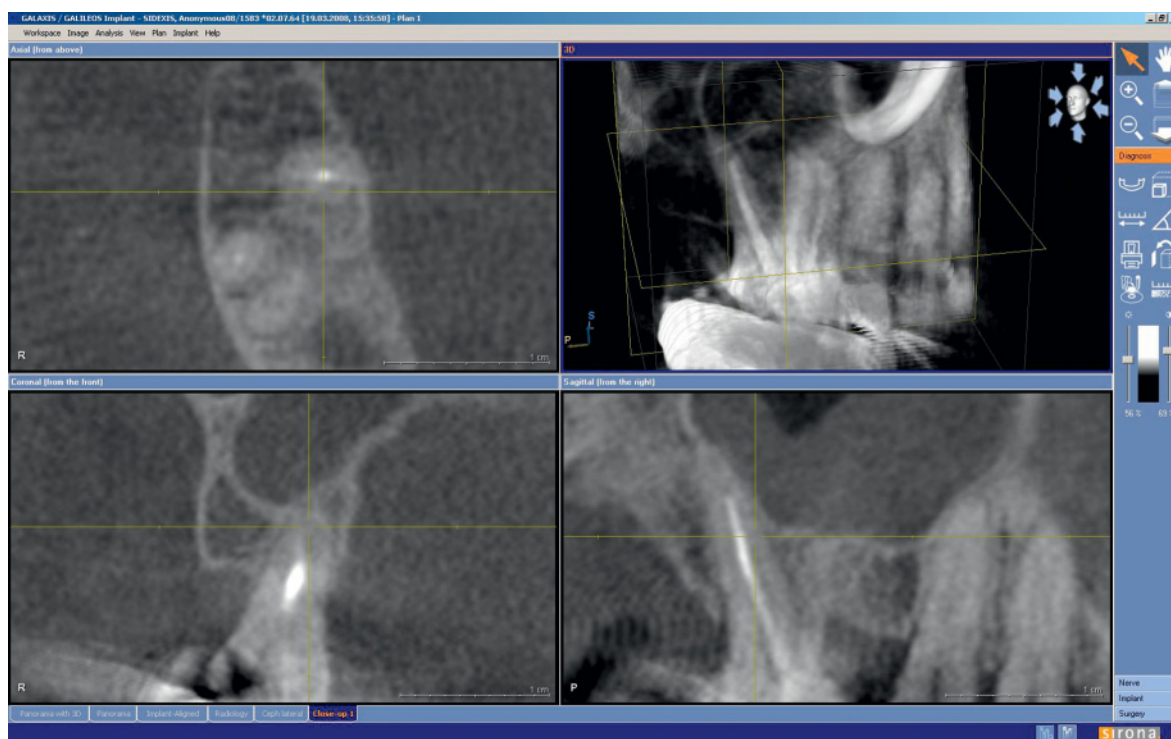


Figure 5.6 Three-dimensional scan of an endodontic filling on tooth 16. Note the incomplete filling from the mesial and distal roots right to the apical delta.

PERIODONTAL LESIONS

With the improvement of dental health and a decrease in the caries-associated loss of teeth, periodontal disease is of increasing significance to our aging societies. As the diagnosis of periodontal disease is established by clinical parameters, treatment planning and recall is supported by X-ray examinations.

For less severe cases, a panoramic scan may be sufficient for periodontal evaluation, but surgically treated patients usually receive a series of 10–14 intraoral images. The intraoral images are much more detailed than panoramic imaging, but, being a 2D imaging modality, an exact representation of the 3D anatomy is not possible. The morphology and size of intraosseous pockets cannot be properly assessed. Discrepancies between the radiologic situation and the intraoperative situation are frequent and significant – radiologic and clinical evaluations agreed in identifying the involvement of the furcation only 43.7% of the time.^{14,28} Moreover, it is hard to standardize intraoral imaging, which biases therapy control.

With the advent of cone beam imaging, the 3D assessment of periodontal defects is within reach for clinical routine. Three-, two-, and one-wall intraosseous defects, as well as furcation involvement, can be visualized (Figure 5.7); Misch *et al.* showed that there is no significant difference in the linear interproximal assessment of bony defects for intraoral and cone beam imaging.²⁹ Regarding radiation dose, cone beam imaging can be considered superior for most machines.

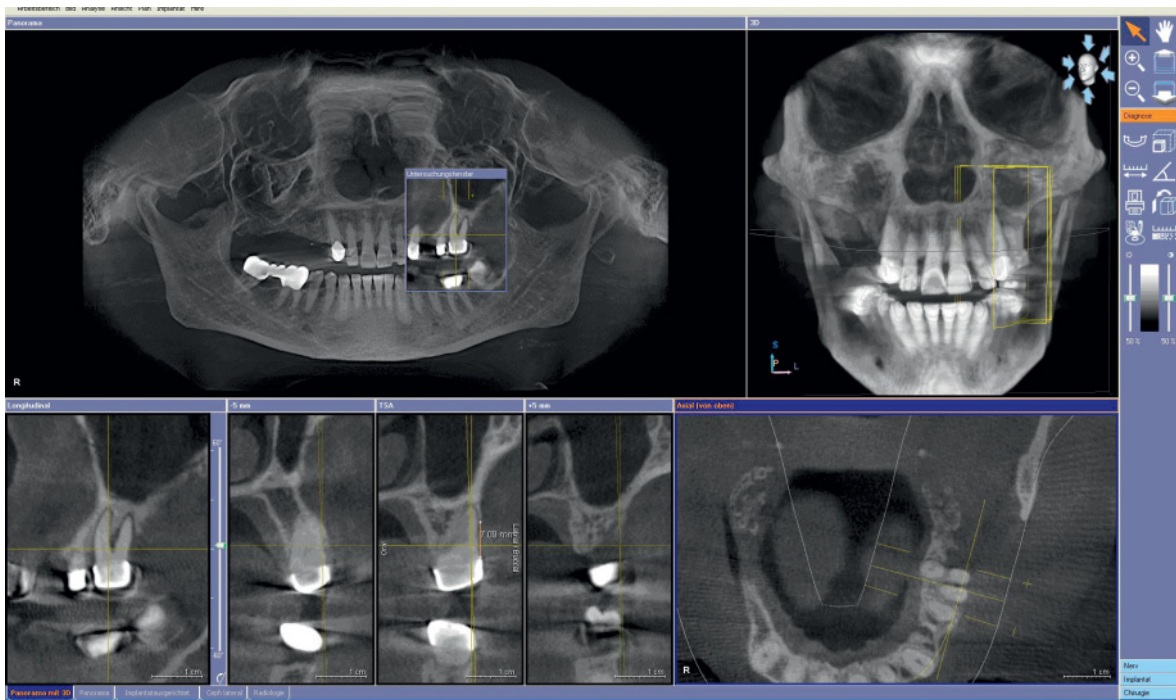


Figure 5.7 Periodontal disease involving the bifurcation of tooth 26. The whole periodontal ligament appears widened. A one-wall defect is visible distally.

IMPLANT SURGERY AND AUGMENTATION

The insertion of dental implants for anchoring dental restorations belongs today to the recognized spectrum of therapy for restoring the mastication and speech function. Implants are used for a wide range of indications, such as implant-anchored single crowns, bridges, or removable dentures. In ideal situations, the implants can be inserted into the remaining local bone.³⁰ However, after the loss of teeth, rapid atrophy of the alveolar process frequently limits the available bone bed, so that accurate orientation is required for the positioning of the implants. This results in a need for augmentation, and this has to be estimated. Once completed, prosthetic treatment can be designed optimally in terms of esthetic and functional aspects.³¹

This spatial orientation is commonly achieved using planning models, a possibly produced wax-up and 2D X-rays. However, this procedure permits no direct superimposition of information from the different diagnostic sources.³² Thus, misinterpretations of the anatomic structures and suboptimal implant positions from a prosthetic standpoint occur. 3D radiologic diagnostics have therefore been recommended for a few years for estimating the accurate anatomic conditions.^{33,34}

If 3D data are available, the use of adequate software tools for the diagnosis and treatment planning of dental implants is suggested. This procedure is especially advantageous if the approach of “backward planning” is followed. In this case, a wax-up is produced and molded in radio-opaque plastic before the radiologic exposure. The patient wears this scanning template containing the spatial information of the

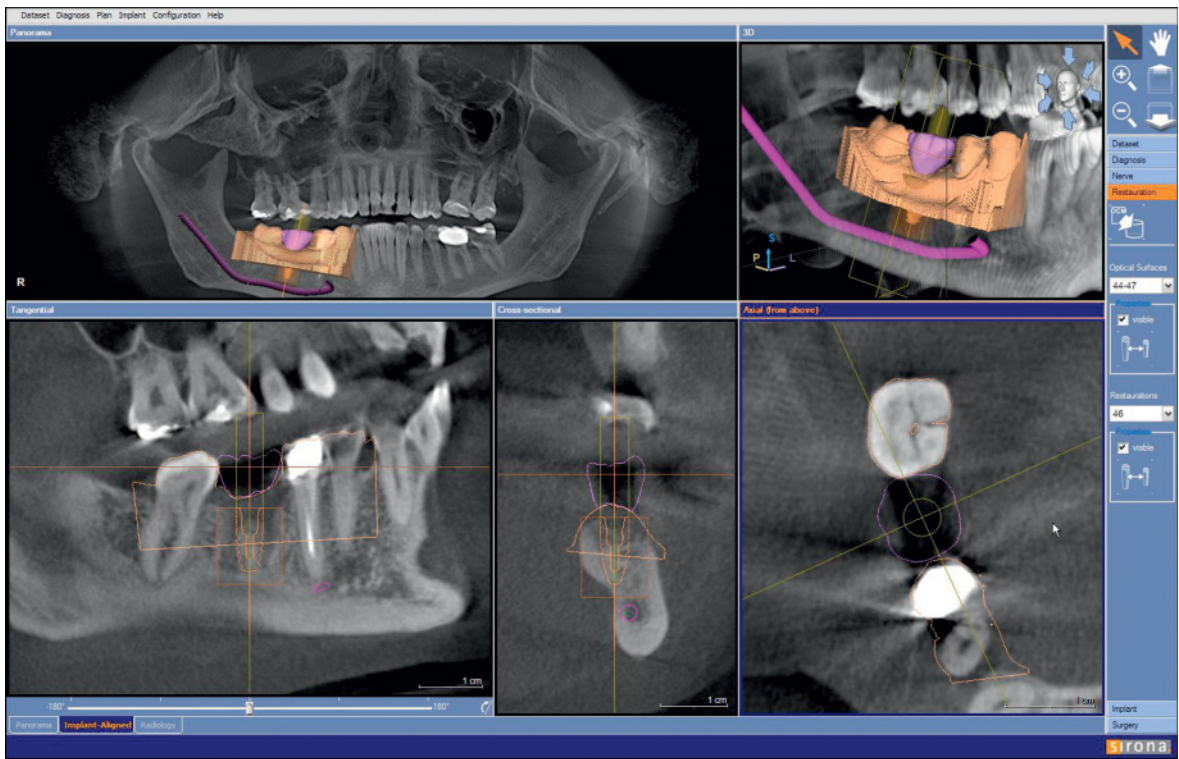


Figure 5.8 Virtual implant planning based on a virtual wax-up and three-dimensional X-ray dataset.

planned prosthetic solution during the exposure, so both the bone situation and the prosthetic planning are subsequently displayed in the radiologic dataset.³⁵ This approach has been established by the first software packages for computer-assisted implant planning introduced in 1997. These systems are characterized in that plans produced on the computer can also be realized intraoperatively with the aid of navigating methods.^{33,35}

Another approach is to acquire a 3D model of the dentition by 3D surface scanning.³⁶ Software tools for virtual prosthetic reconstruction (CEREC, Sirona Dental Systems, Bensheim, Germany) can then be used to produce a virtual wax-up. This virtual model can be integrated into the virtual planning scene and visualized parallel to the X-ray dataset (Figure 5.8).³⁷ This approach offers an advantage over the previous one that implant planning can be readily achieved without external help. Furthermore, provisional prosthesis and drilling templates could be manufactured by computer-aided design/computer-aided manufacturing before the implantation has occurred.

So far, there exist two different technologies for navigation in implant surgery in order to transfer a virtual treatment plan to surgical reality: drilling templates and optical navigation.

Drilling templates

Drilling templates have been established as a straightforward approach for the dental technician. The intraoperative handling is easy and safe. However, two main disadvantages are associated with drilling

templates. One is that they do not permit a change to the planning protocol intraoperatively without totally leaving the guidance of the drill. This might be necessary if the intraoperative situation appears different from the radiologic information on which the plan is initially based. Second, drills extended in length are required to bridge the additional distance from the bone to the drill sleeve, limiting their applicability in the molar region, especially if the patient has a small incisal edge distance.

Presently, drilling templates for computer-guided implant surgery can be manufactured by two different technologies: a stereolithography technique and a computer-aided technique.

Stereolithography-based systems are capable of producing arbitrary 3D geometries using a laser system to cure an acrylic resin on a slice-by-slice approach. On each slice, the laser traces a part-slice pattern on the surface of the acrylic resin. The laser light cures the pattern traced on the resin and polymerizes it to the slice below. After finishing each slice, an elevator platform descends by a single layer of thickness, and a blade sweeps across the part-slice, recoating it with fresh resin. Subsequently, the next slice is cured, finally resulting in a 3D part that then has to be finished by removing the excessive resin and curing in a light oven.

This approach allows the production of templates based on teeth, mucosa, or bone, since the 3D model for the template can be defined from any information contained in the patient's 3D dataset. This implies a close relationship of the reliability of these templates to the quality of the dataset. If artifacts are present in the underlying patient dataset, frequently caused by metallic dental restorations, the image information is hampered and cannot provide the necessary precision for dental implantology. On the other hand, these systems provide a reliable way to treat edentulous patients.^{35,38}

Another approach to producing surgical drill templates for computer-aided dental implantology is to transfer a virtual plan into a conventional drilling template manufactured by the dental technician. For this approach, a coordinate reference system between the radiologic dataset and the template is necessary. Different materials are applied as reference markers, with the common characteristic of being radio-opaque, permitting an automatic or semi-automatic detection of the markers' position in the patient's dataset. Subsequently, a drill, either manual or computer-driven, is registered to the markers present on the physical template. After drilling, a drill sleeve according to the implant system used in the plan is inserted into the drill hole, and the drilling template is finished.

Optical navigation

Alternatively, systems based on optical navigation are applied for computer-aided dental implant surgery. Here, an optical reference is established between the handpiece and the patient and referenced to the radiologic 3D dataset (Figure 5.9). Such systems follow the approach of image-guided surgery and permit the use of an intraoral approach.

The infrared camera tracks the handpiece as well as the patient using optical markers. A direct line of sight between the optical markers and the camera is required to maintain the tracking. The position of the instrument with respect to the underlying radiologic dataset is displayed on the monitor, and this image-guided intervention allows modifications of the original plan, since both handpiece and drill can be moved freely and the corresponding position in the radiologic dataset is displayed.

The disadvantages of these systems include a necessary line of sight from the tracking instrument (i.e., infrared camera) to the handpiece as well as to the patient.³¹ This requirement is frequently hard to fulfill in a clinical environment. Additionally, high costs and the need to fixate the optical reference markers to the patient by some template have limited their spread in dental practice.

One common problem of most available systems is that different individual components of imaging, planning software, and hardware have to be used.³¹ This results in additional interfaces, not only from

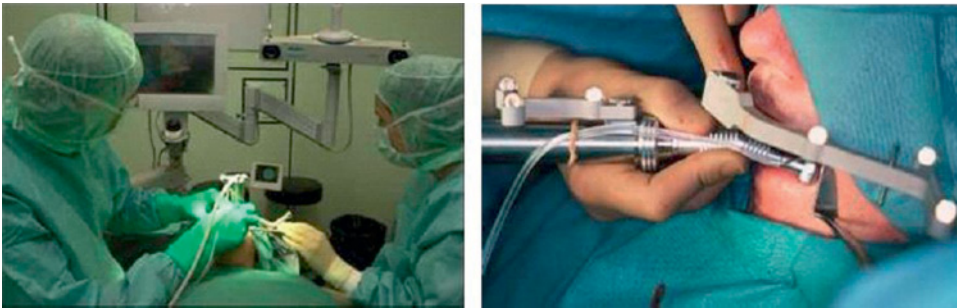


Figure 5.9 Clinical setup for optically navigated implant surgery.

a technical point of view, but also concerning patient management. Apart from the attending surgeon, the dentist, dental technician, and radiologist have to be included in the process chain.³⁹ Furthermore, all components used must interact optimally with one another, and the user must also be able to handle them.

Software features for computer-aided dental implant surgery

The implant planning software should contain realistic displays for all common implant systems in the form of an easily accessible database. Dedicated tomographic views are required for the actual implant planning, so that the implant bed can be checked optimally in all dimensions. Furthermore, a 3D volume overview and panoramic views are required in order to relate the positions of the implants to one another and the given residual dentition. Tools for aligning the implants parallel, the display of a configurable safety distance, as well as graphical highlighting of the inferior alveolar nerve are helpful. When planning toward a surgical template for intraoperative use, it is useful to be able to visualize the following drill canals, dimensions, and position of the drill template to be manufactured.

The handling of such software is critical and should be as intuitive as possible in order to produce an efficient workflow. Therefore, buttons and features in the top layer of the user interface should be as limited as possible in order to avoid user confusion and overload. Imaging and implant planning are optimally accommodated in one software system so that no system change and no conversion or conditioning of data are necessary.³¹

Clinical examples for computer-aided dental implant surgery

Case 1

A 78-year-old female patient presented after extraction of her upper molars on both sides for a prosthetic rehabilitation anchored on implants. The preoperative 3D scan revealed an insufficiently ossified extraction alveolus and a limited vertical bone level, suggesting a sinus lift bilaterally. First, impressions and a bite registration of the patient were taken. A wax-up for the planned prosthetic restoration was then produced in a dental laboratory. The wax-up was subsequently adapted to the patient according to the extent of this prosthetic planning. After the patient had agreed to this prosthetic procedure, the wax-up was converted into a scanning template in which the teeth were represented by barium sulphate-dosed acrylic. The system-specific reference plate with six marker balls was polymerized to the converted

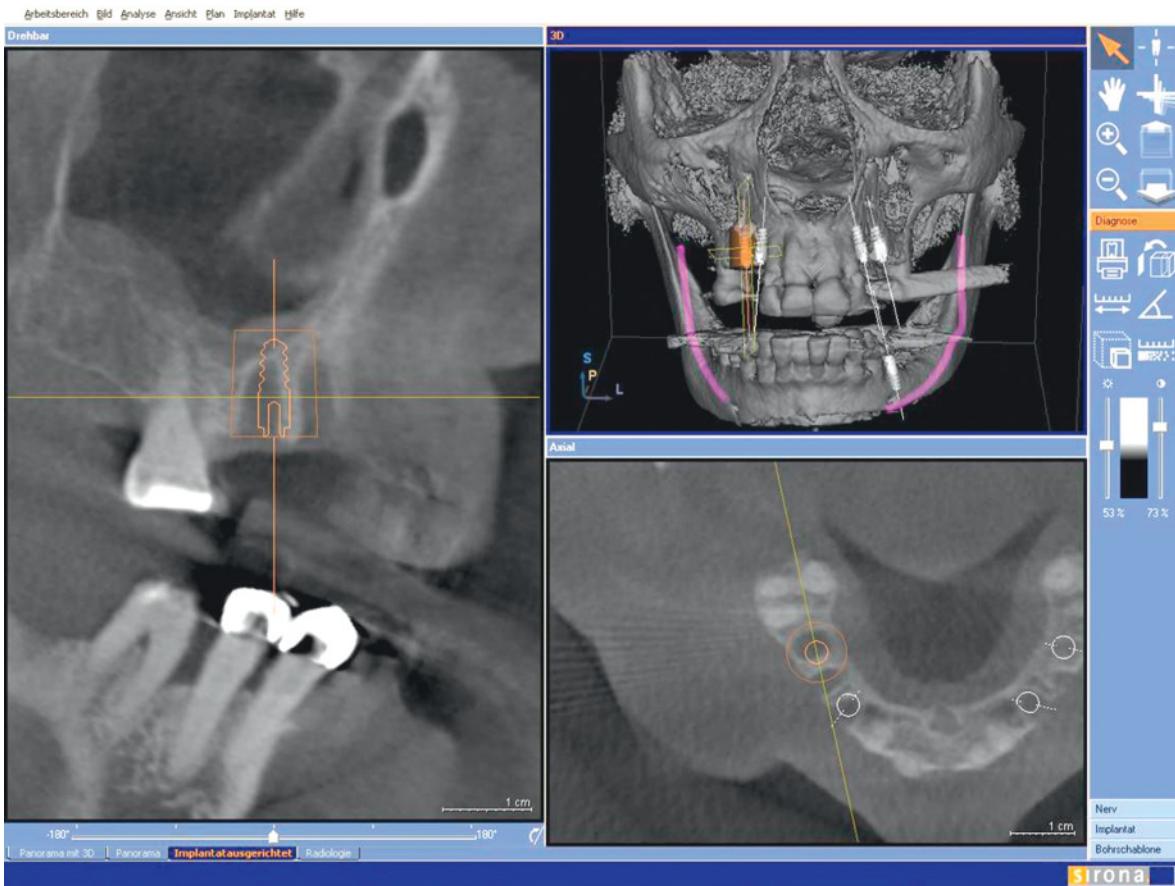


Figure 5.10 Implant planning using GALILEOS Implant (SiCAT, Bonn, Germany). The sagittal slice on the left shows the relation of the planned implant to the sinus as well as the remaining tooth distally. The axial slice on the lower right shows the extent of the implant in the horizontal plane as well as the distances to the mesial implant and the roots of the distal tooth. The surface volume-rendering provides an overview of the overall plan.

wax-up. For the 3D scan, it is important, as in all reference systems, to pay attention to the correct position of the template in the patient's mouth.

After acquiring a 3D CB scan (GALILEOS; Sirona Dental Systems, Bensheim, Germany) with the patient wearing the appliance, the integrated planning software was used for implant planning (GALILEOS Implant; SiCAT, Bonn, Germany; Figure 5.10). A total of four implants were planned, two on each side. The scanned volume of the GALILEOS scanner displays the entire facial skull. The formation of the temporomandibular joint can also be assessed with this scan, which can provide indications of functional overloading and possibly necessary prosthetic measures. However, neither was the case for this particular patient. The tube voltage was 85 kV at 28 mA.

After the implants were defined, the data were transferred to the central drilling template production facility, which produced the pilot drill holes in the reference plate using a computer numerical control milling machine. According to the planned procedure, a provisional restoration was produced with

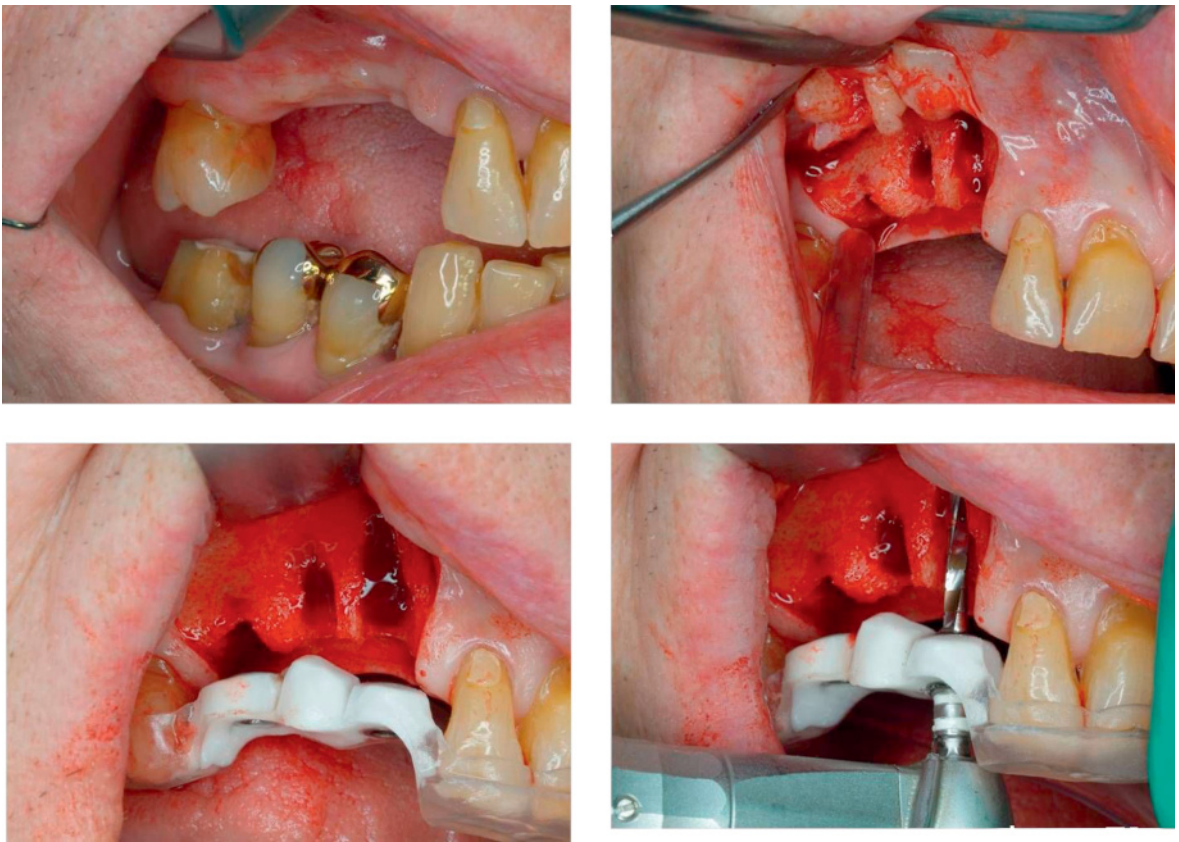


Figure 5.11 Intraoperative handling of the computer-aided design/computer-aided manufacturing drilling template. Note the lowered and customized design of the drill sleeves and the lengthened drill.

assistance from the planning model, and the drilling template was subsequently used for inserting the implants (Figure 5.11). At the time of insertion of the implants, a sinus lift was also performed. After healing for 6 months, the final restoration was inserted (Figure 5.12).

Case 2

A 54-year-old male presented in our clinic for prosthetic rehabilitation. Both his upper and lower jaws had been treated with insufficient removable dentures fixed on telescopes. The underlying panoramic image revealed a total of 17 impacted teeth in the lower and upper jaws (Figure 5.13), aggravating the envisioned implant treatment. Four implants were planned interforaminally in the lower jaw (Figure 5.14), as were an additional two implants in the upper right jaw to support the planned telescopically borne denture. Following the osteotomy of the heavily impacted lower canines, a hip augmentation was carried out to provide an adequate bone bed for the planned four implants.

The planning and manufacturing of the drill guide was achieved as in the previous case. Intraoperatively, the drilling template was set on the remaining lower incisors for fixation, and the pilot holes were drilled

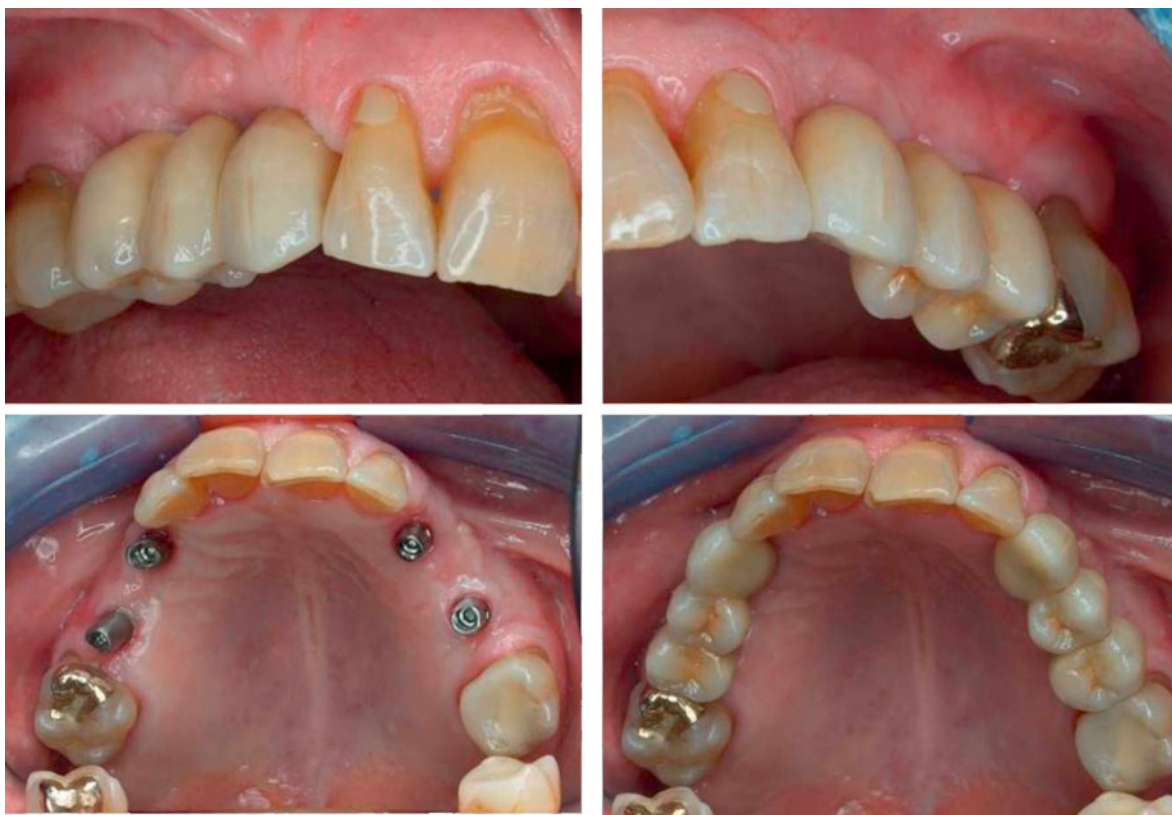


Figure 5.12 Prosthetic result in the upper jaw.



Figure 5.13 Preoperative panoramic X-ray showing impacted teeth in the lower and upper jaws. Following a prosthetic wax-up and a three-dimensional scan, as described in the first case study, it was decided to place a total of six implants, after removal of the lower impacted canines and the three remaining lower incisors.

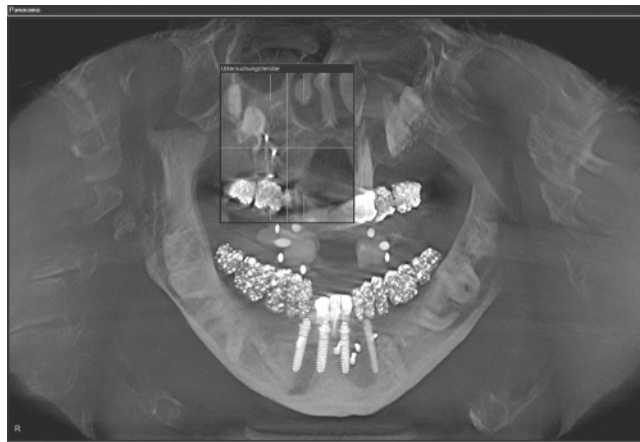


Figure 5.14 Reconstructed pan from the three-dimensional scan showing the barium sulphate prosthetic proposal and the planned interforaminal implants.

for the distally planned implants. Temporary bars were inserted in these, and the remaining incisors were extracted. After extraction, the drilling template could be fixed on the temporary bars, the implant sites for the two mesial implants were prepared, and the implants were placed in position. A temporary prosthesis was positioned in the lower jaw fixated on ball anchors, followed by the final bar-borne prosthesis after 4 months' healing time (Figure 5.15).

Conclusion

3D imaging is helpful for planning most implants. Apart from assessing the necessity for or extent of an augmentative measure beforehand, difficult anatomic conditions can be accurately evaluated by 3D imaging to avoid surgical or prosthetic complications. Thus, the necessary surgical treatment can be designed to be as minimally invasive as possible. Thanks to the computer-animated true-to-scale display of the individual anatomic conditions, the patient can be informed simply about the required surgical procedure and the resulting course of treatment. In particular, the course of the nerve in the retromolar region for bone harvesting and the configuration of the maxillary sinus floor for sinus floor elevation can be measured and shown to the patient, fostering patient–doctor communication. In this way, the risks, benefits, and possible complications can be described accurately and efficiently to the patient.

The use of 3D imaging is highly recommended in complex cases of changed or atypical anatomy, for example after an accident, tumor resection, or extensive reconstruction of alveolar ridge defects. Depending on the morbidity of the patient, the normally necessary augmentation can also be avoided by corresponding preoperative diagnostics, since the available bone substance can be utilized optimally and thus implants can be inserted in an area with only slight but nevertheless sufficient bone coverage.

3D implant diagnostics by means of cone beam technology allows a comprehensive radiologic diagnosis with a reduction of the radiation exposure in comparison to CT.⁴⁰ Despite the lower radiation exposure, the accuracy of cone beam imaging comparable to CT is shown for hard tissue diagnosis due to its computer-assisted dynamic diagnostic facility.³⁴

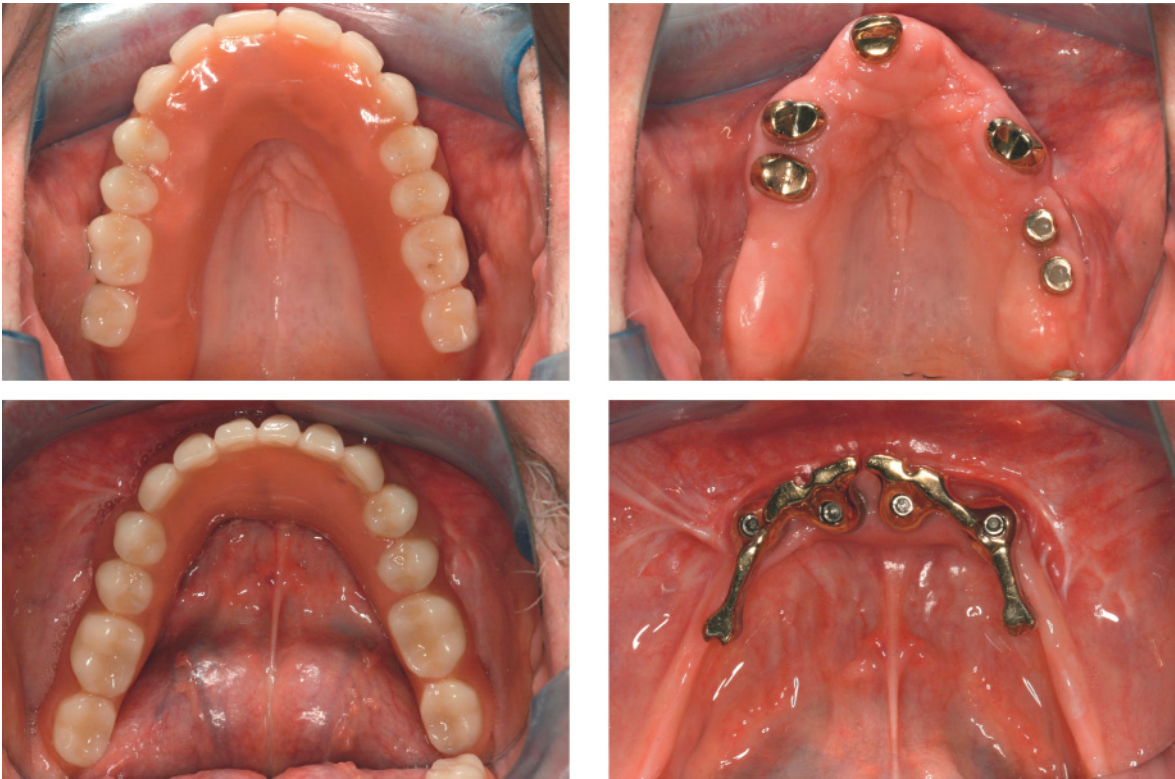


Figure 5.15 The final prosthetic situation after the healing period.

Thanks to the possibility of implementing this technology in dental practice, the data are available directly after performing the scan. This enables the dentist to use this technology for further therapy planning and for consultation at the time of diagnosis. In this way, a further consultation with the patient becomes superfluous and the effectiveness of clinical practice is increased. 3D diagnosis further facilitates optimum preparation for the surgical intervention, since intraoperative findings are commonly detected in advance. Since no second or additional planes, as for conventional radiographs, have to be produced, the total number of radiologic exposures is reduced. The trend for dentists to work in joint practices or to be employed in centres also economically justifies the high procurement costs.

A main indication for using 3D planning today is immediate loading.⁴¹ With corresponding planning, a provisional restoration can already be produced beforehand and be incorporated right after the insertion of implants. Besides the high patient satisfaction, this procedure facilitates the treatment, since stages of work that normally follow on after insertion of the implant can already be completed before the surgical operation.

When microimplants are used, the 3D template technique allows support indirectly on the bone, further increasing precision. Thanks to the early inclusion of the dental technician in case planning, the final treatment can be achieved with less need for communication during the rest of the course of the restoration. There are also lower costs for the preparation of the abutments.

For systems based on stereolithography, there is increased expense for segmentation (i.e., determination of anatomic structures in the 3D dataset), which is also undertaken partially centrally. Some systems even require a double scan of the template or of the prosthesis with reference marks, which means increased radiologic expense and possible registration errors, especially when performed in a radiologic practice less experienced in dental implant planning. Other systems offer integrated diagnostic and planning software in which segmentation is no longer necessary. Therefore, implant planning can follow directly after diagnosis using the same software, superseding further interfaces and data conversion. On the other hand, stereolithographically built templates offer the possibility to be bone-borne. Common to all surgical templates is the limited use in the molar region due to spatial constraints. However, the use of a drilling template demonstrates the possibility of an accurate implementation of planning with preparation of the dental laboratory work especially for immediate loading.

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6

Referencing and Registration of Three-Dimensional Images

Lucia H.S. Cevidanes, Martin Styner, and William R. Proffit

INTRODUCTION

Two-dimensional (2D) cephalometric representations of the three-dimensional (3D) craniofacial structures cannot answer the many questions regarding treatment response mechanisms and localization of growth.^{1,2} However, 3D assessments pose a significant challenge in the choice of superimposition of landmarks and/or structures. Superimposition of serial radiographs onto a stable reference structure is necessary to evaluate growth or treatment change. 3D imaging from cone beam computed tomography (CBCT), axial CT, magnetic resonance imaging, or surface laser scans offers improved diagnostic information and, perhaps more importantly, also provides a better way to evaluate the changes created by treatment and the skeletal and soft tissue adaptive responses to treatment that occur.³⁻¹⁰ In 2D cephalometrics, the cranial base often is used for this purpose because it shows minimal changes after neural growth has been completed.

REGISTRATION ON 3D SURFACES VERSUS LANDMARKS

Although landmark location in 2D is hampered by the identification of hard and soft tissues on radiographs due to the superimposition of multiple structures, locating 3D landmarks on complex curving structures is significantly more difficult. As Bookstein noted,^{11,12} there are no suitable operational definitions for craniofacial landmarks in the three planes of space (coronal, sagittal, and axial). In the context of facial changes, superimposition should not rely on landmark identification or on best-fit techniques on structures that change over time with growth and treatment. Maxillomandibular changes need to be assessed relative to stable structures that have not been altered with growth or treatment.

To better understand soft and hard tissue facial forms and changes with growth and treatment, as well as to create normative databases and predict changes, registration on the whole surface of the cranial

base is the best method. This chapter demonstrates the use of a fully automated voxel-wise rigid registration at the cranial base and the application of 3D superimposition methods to evaluate anatomic structures displaced by growth, surgery, or other treatment.

METHODOLOGY FOR SURFACE REGISTRATION

CBCT equipment specialized for maxillofacial imaging now offers a relatively low-dose and convenient way to follow changes in facial morphology in three dimensions. The use of 3D images for treatment planning and follow-up raises concerns regarding the radiation dose. CBCT scans of the cases presented were acquired with the NewTom 3G (AFP Imaging, Elmsford, NY, USA), with a $36.3\mu\text{Sv}$ acquisition dose for a maxillary and mandibular scan. This is a major reduction from $314\mu\text{Sv}$ for conventional axial CT. There is a decrease in the signal-to-noise ratio with CBCT, but there is complete visualization of the facial structures with spatial resolution of 0.36 mm in isotropic voxels. The imaging protocol utilized a 12 inch field of view to include the entire facial anatomy.

The analysis of serial CBCT images to evaluate changes over time is undertaken in a sequence of four steps, described below.

Construction of virtual 3D surface models

Currently available commercial software does not allow the construction of virtual 3D surface models, but rather displays a 3D rendering that is a projection of the 3D structure of the face for visualization purposes. The implementation of registration tools using best-fit between the 3D renderings does not allow the quantification of local changes with treatment, but would allow an overall visualization. Longitudinal quantitative assessment of growth and surgical correction requires the construction of 3D surface models. The image analysis tools for this purpose are modifications of open source, freely available software from the National Institutes of Health (Bethesda, MD, USA).

Segmentation, that is, outlining the shape of anatomic structures visible in the cross-sections of a volumetric dataset from CBCT images, is performed with the ITK-SNAP tool,¹³ which is a freely available open-source program. ITK-SNAP is a tool for viewing 3D images and delineating and extracting anatomic structures, and it allows simultaneous visualization, navigation, and segmentation of all three planes (axial, sagittal, and coronal) with a linked cursor system that allows the tracking of a single voxel.

Segmentation can be completed using two different modes: semi-automatic segmentation and manual segmentation. In the semi-automatic mode, segmentation employs an algorithm that allows a deformable bubble to grow to define borders between neighboring anatomic structures. Many standard automatic segmentation methods fail when applied to the complex anatomy of patients with facial deformity. The methods described by Gerig and co-workers address these technical difficulties, and have been adapted by Cevitanes and co-workers to construct 3D craniofacial models.^{14,15}

The 3D virtual models are usually built from a set of around 300 axial cross-sectional slices for each image, with the voxels reformatted for an isotropic of $0.5 \times 0.5 \times 0.5\text{ mm}$. This resolution is used because although higher spatial resolution with smaller slice thickness is possible, it increases the image file size and requires greater computational power and user interaction time without significantly improving the quality of assessment of changes between time points. After segmentation with the ITK-SNAP tool, these files are converted from volumetric data into surface meshes for the 3D shape analysis procedures.

Registration of longitudinal 3D CBCT images and surface models

This is a core technology to assess growth and treatment outcomes that can involve nonrigid or rigid registration procedures. Nonrigid procedures can be used to assess across patient differences in size and morphology. The two obstacles to the widespread clinical use of nonrigid (elastic and deformable) registration are computational cost and quantification difficulties as the 3D models are deformed. Nonrigid registration would be required to create a composite of several different jaw shapes to guide the construction of template or standard normal 3D surface models. However, to evaluate longitudinal changes, a rigid registration of CBCT images is acceptable, and establishes a common coordinate system in which longitudinal changes can be assessed.

To use only stable structures and avoid observer-dependent techniques based on anatomic landmark identification, we mask anatomic structures displaced with growth and/or treatment and then perform a fully automated voxel-wise rigid registration at the cranial base, using rigid registration and Imagine software.¹⁶ Rotation and translation parameters are calculated and then used to register 3D models from before and after treatment on the cranial base (Figures 6.1 and 6.2).

For the registration of CBCT scans of subjects in whom cranial base growth is complete, registration of virtual 3D surface models is done utilizing the whole surface of the cranial base (Figure 6.3). To evaluate within-subject changes with growth and treatment, the endocranial surfaces of the anterior cranial fossae and the ethmoid bone are used in the registration procedure, since the growth of these structures is completed in early infancy. In this way, the anterior cranial base of the CBCT images is used as the reference for superimposing different time points. Maxillomandibular changes are described not as absolute displacement, but as displacement relative to the cranial base (Figures 6.3 and 6.4).

Superimposition of 3D surface models

After registration, the overlay of the 3D models can be assessed using a number of different publicly available tools, such as Slicer3, Vol2Surf, FltkSOV3Dtool, Valmet, and MeshValmet developed by the National Institutes of Health roadmap National Alliance of Medical Computing, of which University of North Carolina (UNC) is part.

The next step in the analysis involves overlaying the 3D model surfaces that are registered in the same coordinate system with another tool, CMF software (Maurice Müller Institute, Bern, Switzerland).¹⁷ This tool allows different degrees of transparency to visually assess the boundaries of the maxillomandibular structures between superimposed models at two different time points. This clearly identifies the location, magnitude, and direction of mandibular displacements, and also allows a quantification of the vertical, transverse, and anteroposterior bone displacements and remodeling that accompany growth and response to treatment.

Visualization and quantitative assessment of changes with growth and treatment

Precise quantitative measurement is required to assess the changes resulting from growth and treatment. For example, in the evaluation of surgical treatment, we need to identify the placement of bones in the desired position, the sites of surgical cuts, fixation of screws, and/or plates relative to risk structures, and the location and amount of post-treatment bone remodeling. Landmark-based measurements reflect errors related to landmark identification. The use of semi-landmarks has been proposed, that is,

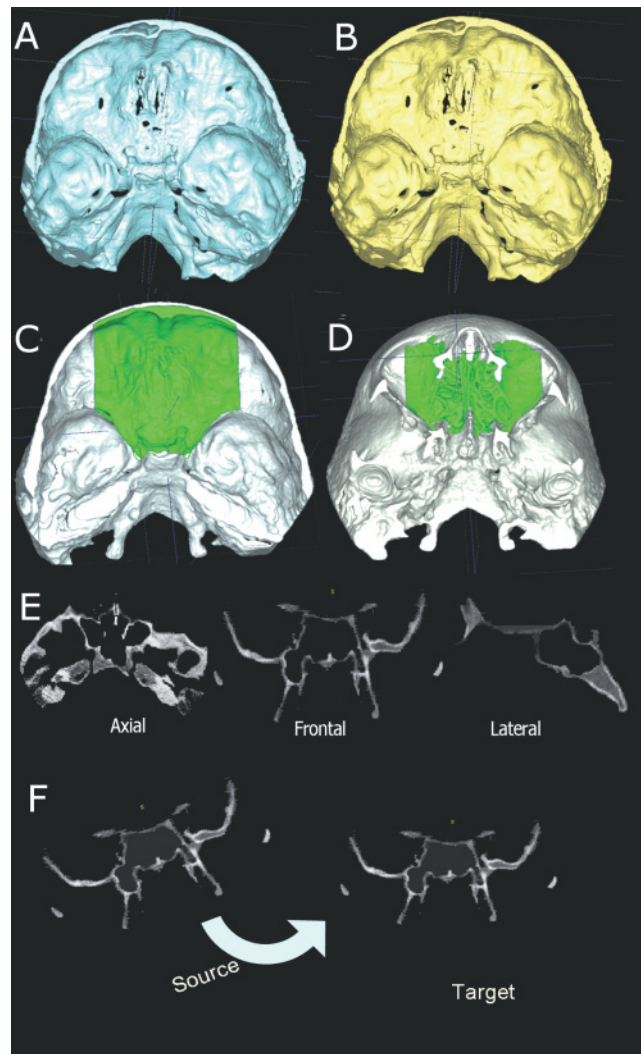


Figure 6.1 The superimpositions of three-dimensional models of growing children differ from those of adult patients. (A, B) Superimposition of three-dimensional surface models of a nongrowing subject in which we use the whole surface of the cranial base for registration of the before- (A) and after- (B) treatment images. (C, D) Superior (C) view and inferior (D) view of three-dimensional surface models after treatment that were used for assessing growth/treatment changes. Note that, for growing subjects, the anterior cranial fossa surface has been used for registration because this area has completed growth in early infancy, in such a way that the superimpositions describe growth relative to the individual cranial base. (E) Gray level intensity image containing only the cranial fossa for the calculation of registration parameters. (F) Fully automated calculation of rotational and translational parameters between the images.

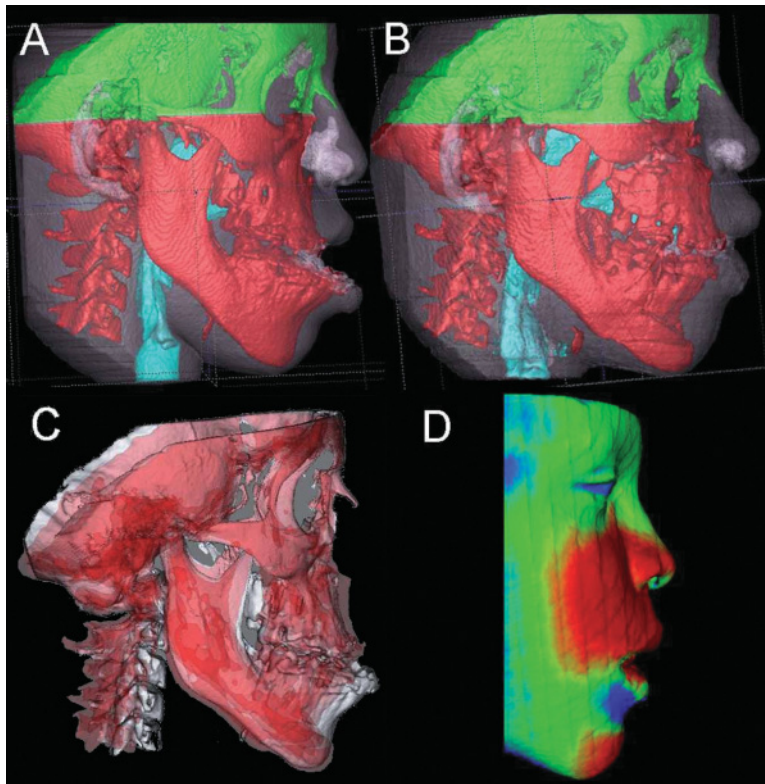


Figure 6.2 (A) Before treatment and (B) at 1 year follow-up of treatment on a surgical patient. (C) Visualization of skeletal changes from (A) (in white) and (B) (in red) superimposed on the cranial base with semi-transparency. (D) Quantification of soft tissue changes for this case using surface distances color maps.

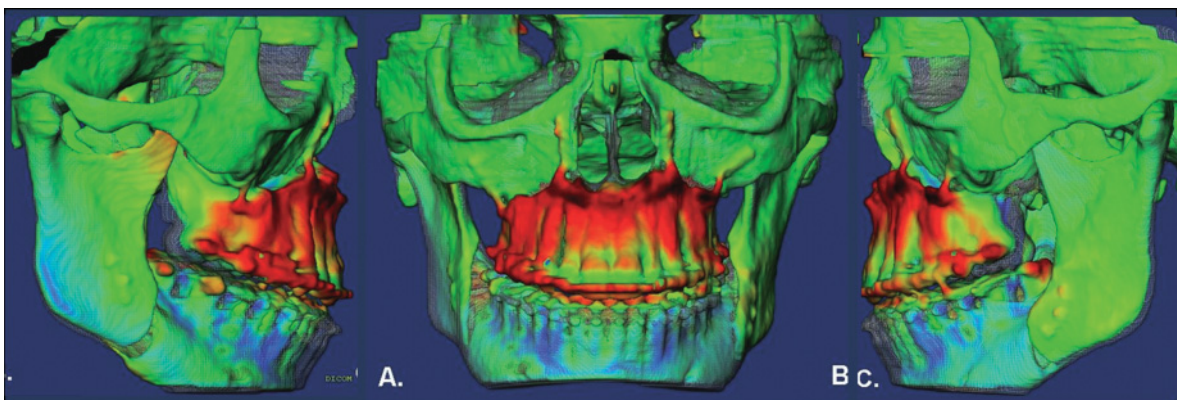


Figure 6.3 Superimposition of pre- and post-surgery models of a nongrowing patient showing the surface distances between two models. The surface of the cranial base was used for registration. The cranial base color map is green (0mm surface distance), showing an adequate match of the before and after models for cranial base structures. Note that the maxilla was brought forward, as shown in red. Mandibular setback precisely maintained the position of the rami, sliding the mandibular corpus posteriorly, with a slight counterclockwise rotation to correct an open-bite tendency.

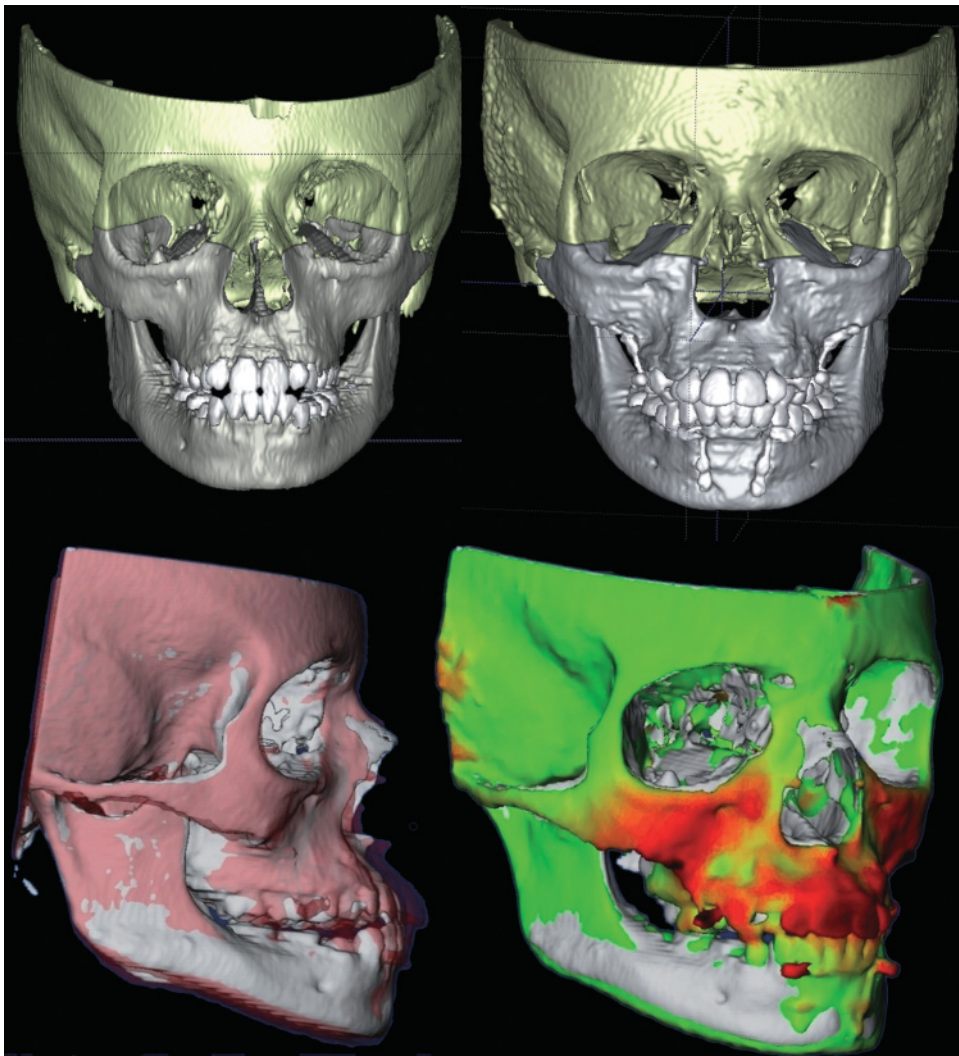


Figure 6.4 Superimposition of pre- and post-treatment models of a growing patient registered on the anterior cranial fossa. (Top row) Initial and final three-dimensional models for a Class III patient treated with skeletal anchorage for the orthopedic correction. (Bottom row) The three-dimensional models on the left show the semi-transparent overlay with the initial model in white and the final model in red. The models on the right show the initial model in white and the final displaying the color map of change. The cranial base color map is green (0mm surface distance), showing an adequate match of the before and after models for cranial base structures. Note that the maxilla was brought forward, as shown in red (5mm).

landmarks plus vectors and tangent planes that define their location, but information from the whole curves and surfaces must also be included.^{18,19}

Accurate quantitative measurement is required to assess growth and bone remodeling. Iterative closest point is the approach used by most commercial and academic software programs for post-treatment assessments. Commercial software programs, such as Geomagic (Geomagic, Inc, Research Triangle Park, NC, USA), Analyze (Visage Imaging Inc, San Diego, CA, USA), 3dMD Vultus (3dMD, Atlanta, GA, USA),

and Amira (Visage Imaging Inc, San Diego, CA, USA), produce excellent surface reconstructions, but are not open source and do not address the 3D correspondence problem across patients with different facial morphology, or between pre- and post-treatment scans of the same patient.

The methods in this chapter measure closest distances using academic and publicly available software to quantify skeletal dental and soft tissue positional changes as well as bone remodeling with growth and treatment. The use of color maps generated from closest-point distances between the surfaces has been proposed.¹⁵ Even though this method measures closest distances (not necessarily landmarks), the corresponding distances between anatomic points on two or more longitudinally obtained images, using the MeshValmet and CMF tools, allow the calculation of thousands of distances in millimeters between a surface's triangles at two different time points, so that the difference between the two surfaces at any location can be quantified. After combining all the 3D models at various time points, specific regions of interest such as the anterior surface of the maxilla, chin prominence, condyles, and posterior border of the rami can be selected and analyzed (Figure 6.5).

The quantitative changes are visualized using color maps, which can be used to indicate inward (blue) or outward (red) displacement between overlaid structures. An absence of displacement is indicated by

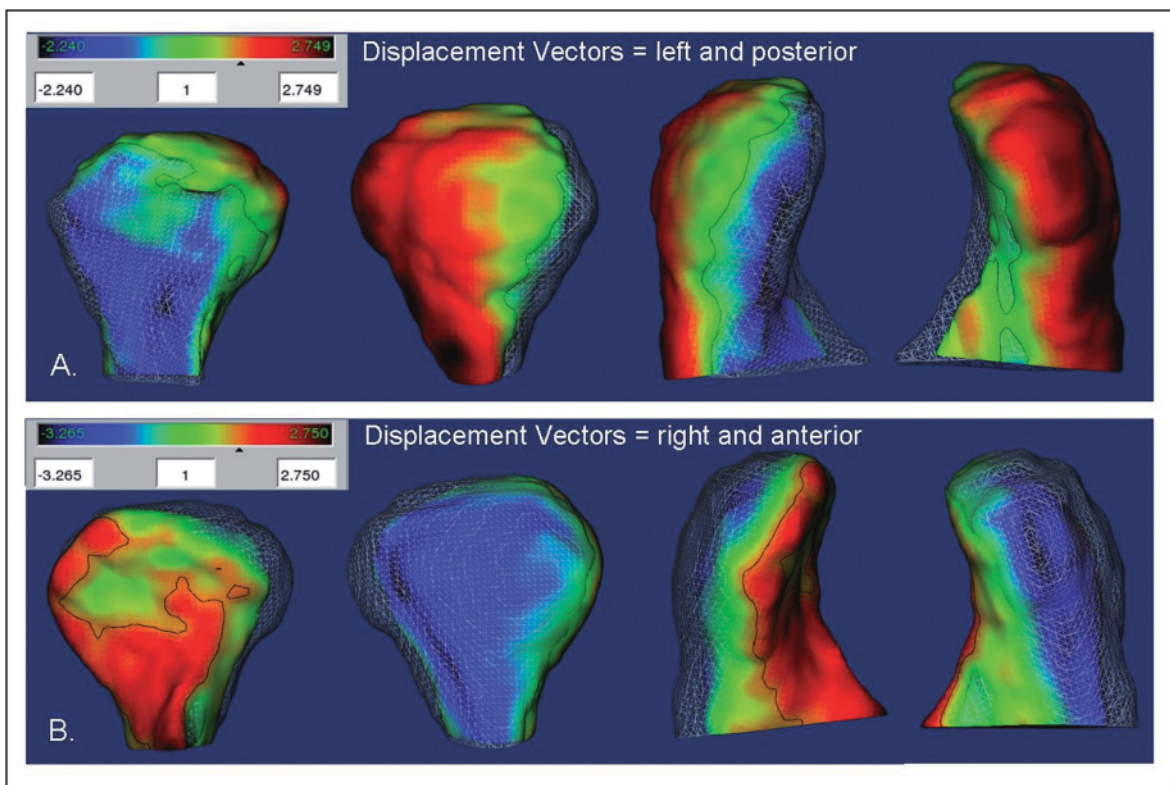


Figure 6.5 The direction of displacement of a specific anatomic region (left mandibular condyle) is clearly identified with the methods described in the text. A color-coded display of displacement showing rotation of the medial pole inward when the mandible was advanced (A), and outward if the mandible was set back (B).

the green color code. For example, in mandibular advancement, forward displacement would be shown in a red color code for the anterior surface of the chin, and a blue color code for the posterior surfaces. A medial displacement of the condyles and rami would display red medial surfaces and blue lateral surfaces. Lack of change would be shown as a green color. This method has been validated and used since 2005.

However, it is very important to realize that displacements in the same direction can be seen as opposite colors depending on their position in the anatomic structures. For example, in Figure 6.4 even though the whole surface of the condyles was displaced posteriorly, the anterior surface appears as blue and the posterior surface is red, with green surfaces in between. Without a careful understanding of what the color maps are showing, this patient could be described as having resorption at the anterior mandibular surfaces and apposition at the posterior condylar surfaces, when in reality posterior repositioning of the entire mandible has occurred. Color maps are a helpful aid in assessing outcomes but require a basic understanding of what they are truly reporting, and care must be taken to not make incorrect interpretations about what has actually occurred. Both hard and soft tissue surface changes can be assessed.

An alternative way of displaying the treatment change is to superimpose both models and modify the final model to be semi-transparent so that the underlying initial model can be visualized (Figure 6.6).

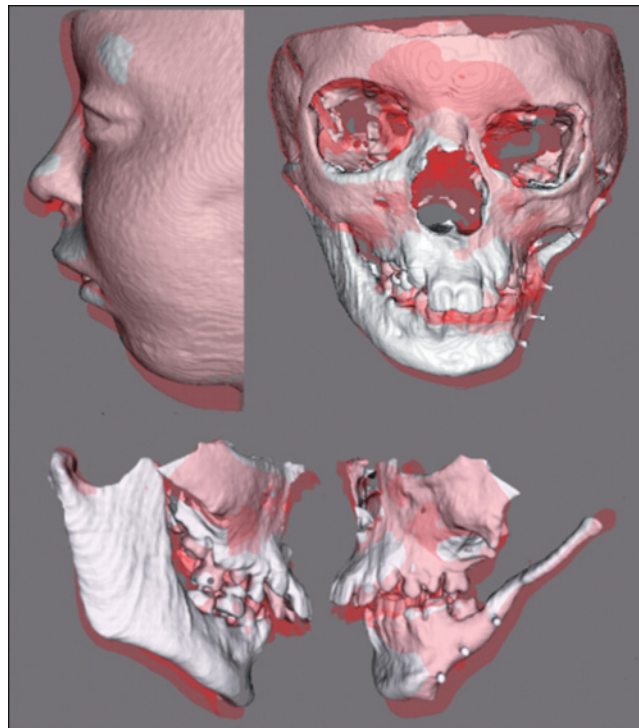


Figure 6.6 Growth superimpositions of a period of 1.5 years during the ascendant part of the pubertal growth spurt curve of a patient with hemifacial microsomia that received a costocondral graft at 7.5 years old. Registered on the anterior cranial fossa, the 3D models on the left show vertical and lateral growth through the semi-transparent overlay. The models in white were taken at age 9.5 years and those in red at 11 years.

POST-SURGICAL TREATMENT OUTCOMES FROM 3D REGISTRATION ON THE CRANIAL BASE SURFACE

We have used longitudinal CBCT images to evaluate post-surgical changes in the position and contours of the maxilla and mandible (including changes in the location and shape of the condyles) relative to the registration on the cranial base surface. Longitudinal CBCT scans before surgery, immediately after surgery, at splint removal, and at 1 year after surgery allow a comparison of changes between any selected times (Figures 6.7 and 6.8, and see Figures 6.3 and 6.5). Rotation of the mandibular rami results in short-

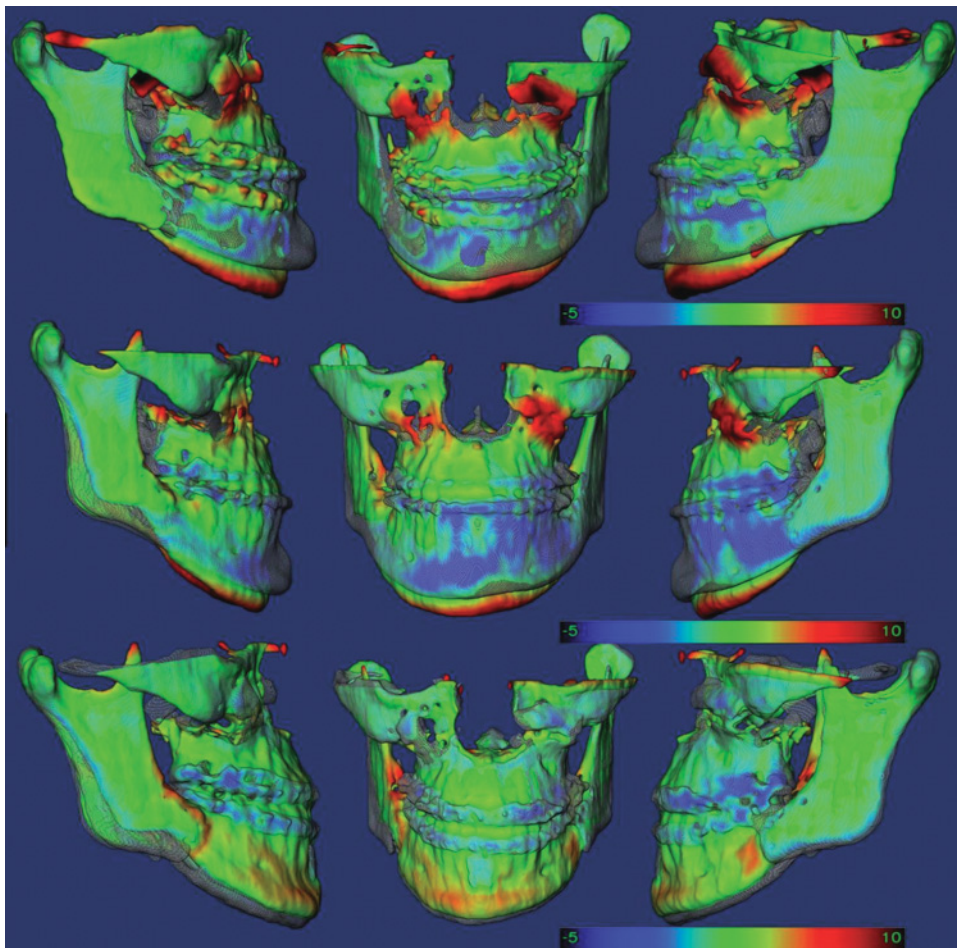


Figure 6.7 Pre-surgery, surgical splint removal, and 1 year post-surgery three-dimensional models of a patient treated with maxillary advancement and mandibular setback. (Top row) Superimposition of the pre-surgery (transparent) and post-surgery (color map) models at splint removal showing the surface distances between the two models. The surface of cranial base was used for registration. Note that the maxilla was brought forward and downward, as shown in red. Mandibular setback precisely maintained the position of the rami, sliding the mandibular corpus posteriorly. (Middle row) Surface distances between the pre-surgery (transparent) and 1 year post-surgery (color map) models show the maxillary advancement and mandibular setback. (Bottom row) Surface distances between the splint removal (transparent) and 1 year post-surgery (color map) models show the mandibular ramus and corpus adaptation following surgery.

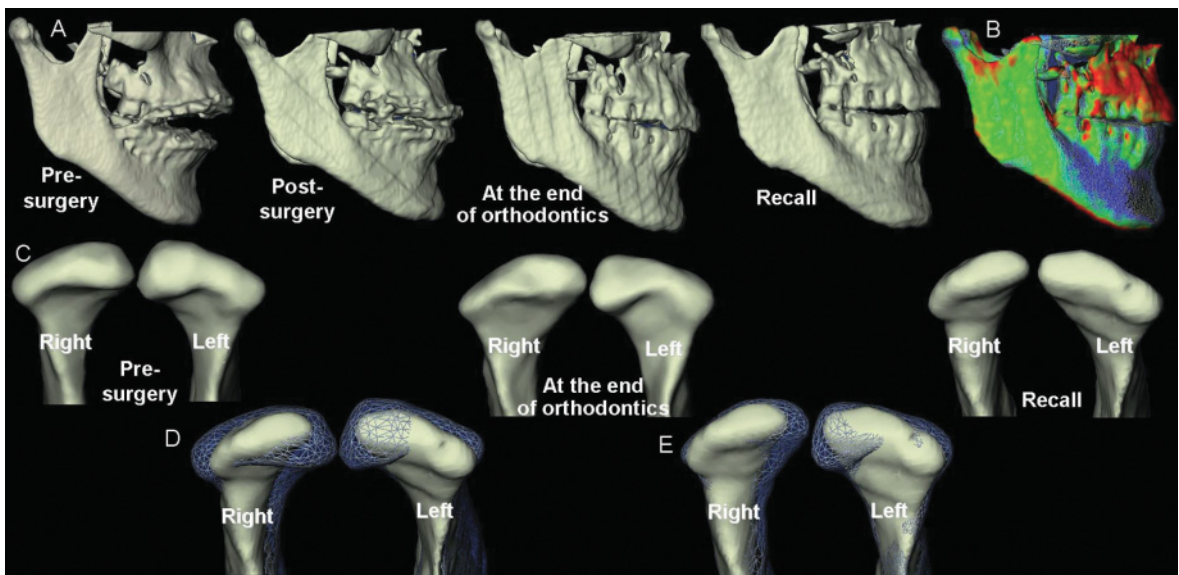


Figure 6.8 Marked remodeling between the end of orthodontics and recall (1 year after the completion of orthodontics). This patient received maxillary impaction for the correction of an open bite. (A) Images from before surgery through recall (1 year after orthodontics). (B) A three-dimensional surface distances color map shows marked remodeling between the end of orthodontics and recall 1 year later. (C) A frontal view of condylar morphology from prior to surgery through to recall. Note that condylar flattening was present in both the right and left condyles before surgery and was more severe on the right. Condylar flattening progressed during post-surgery orthodontics and after treatment had been completed. (D) Superimposition shows remarkable condylar remodeling between the pre-surgery (transparent mesh lines) and recall (surface models) time points. (E) Superimposition shows the progression of condylar remodeling after the completion of orthodontic treatment.

and long-term changes in the spatial position of the chin that can contribute to or diminish the surgical correction (Figure 6.7). Small condylar displacements and modest remodeling of the condyles (mean surface distances of less than 2mm) are observed in most patients after both mandibular advancement and two-jaw Class III surgery, but individual cases show significant condylar remodeling with net resorption after mandibular surgery (Figure 6.8).

When only maxillary surgery is done, the mandibular condyles change position if there is any vertical change (as almost always is the case) by rotating around their long axis. This requires remodeling of the condyles.¹⁹ When a mandibular ramus osteotomy is undertaken, the condyles must rotate transversely (across the long axis) a few degrees when the condylar and tooth-bearing segments are reconnected. The rotation of the medial pole is inward if the mandible is advanced (see Figure 6.5A), and outward if the mandible is set back (see Figure 6.5B).

Remodeling begins quite soon after surgery. Changes can be visualized at 6 weeks (and probably earlier), but remodeling continues throughout the first year. For example, 2D measures might indicate an increase in mandibular skeletal length and an increase in the mandibular plane angle 2 years after surgery that negate the outcomes after mandibular surgery. However, 3D image analysis can establish whether the observed 2D changes are actually due to remodeling on the posterior surfaces of the

mandibular condyles with an accompanying rotation of the mandibular rami unilaterally or bilaterally, or to remodeling at the surgical site. Currently, there is insufficient evidence to indicate whether differently shaped mandibular rami and condyles might dictate different surgical approaches.

CLINICAL APPLICATION AND FUTURE INVESTIGATIONS

Analysis of 3D CBCT images is much more complex than analysis of 2D cephalometric radiographs. Superimposition on landmarks, the usual method, is not satisfactory in the analysis of 3D images, as the cephalometric landmarks cannot be found consistently because images are rotated away from the mid-sagittal plane. With the method developed at UNC, a cranial base superimposition based on the surface contours of the bone overcomes this landmark problem.

In essence, instead of three or four landmark points, as in Figure 6.9, the superimposition is based on thousands of points.¹⁴ This allows a detailed analysis of surface contour changes in the position of both

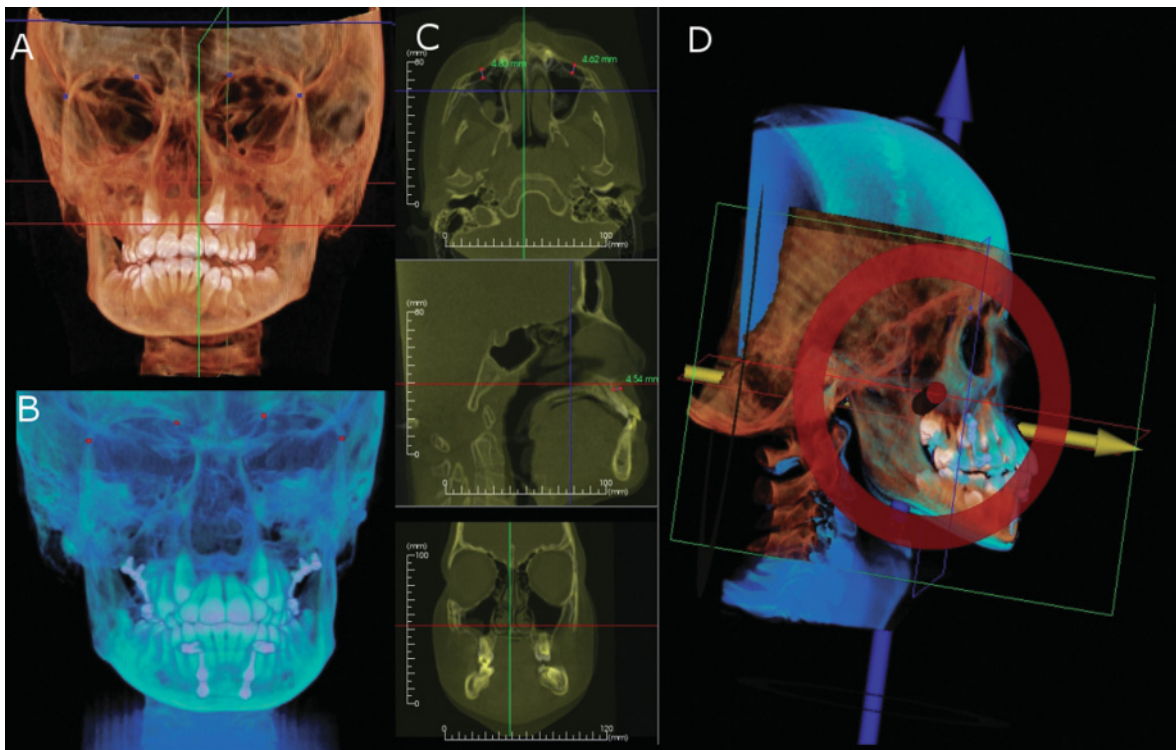


Figure 6.9 Superimposition with Invivo Software 3.1 (Anatomage, San Jose, CA, USA). Choice of three-dimensional (3D) landmarks on 3D surface rendering to register (A) before-treatment and (B) after-treatment 3D renderings. (C, D) Manual adjustment of the x, y, and z-axis to superimpose 3D renderings with visualization of maxillary advancement after manual registration on the cranial base. Note that a quantification of changes can only be made in two-dimensional cross-sectional slices and that the registration is not adequate in all three planes, as shown in the anteroposterior cross-section.

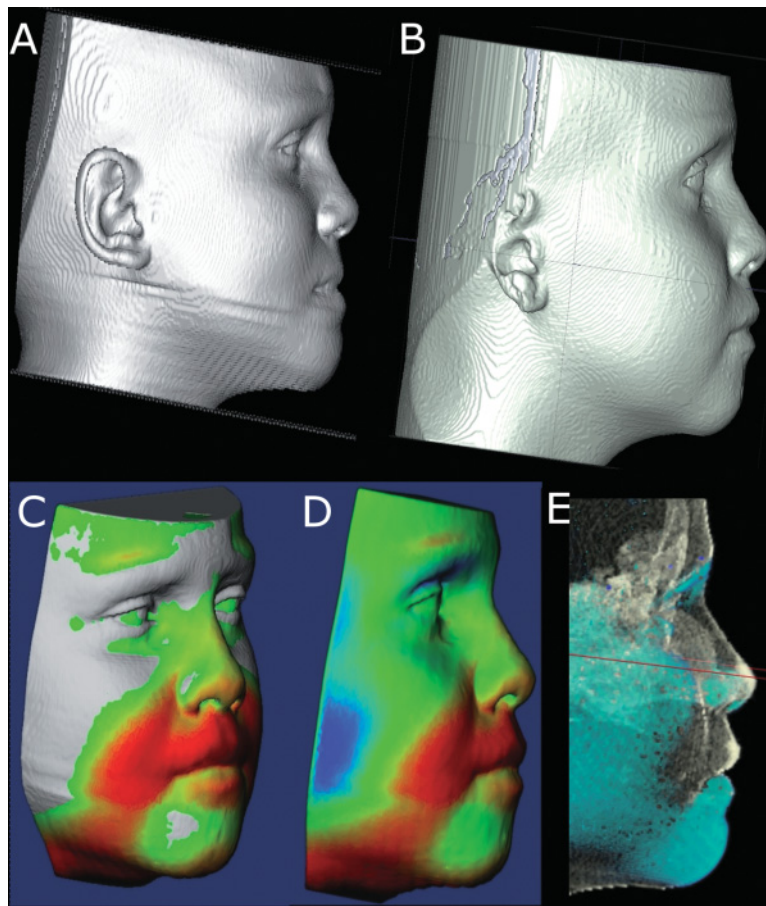


Figure 6.10 Visualization of soft tissue changes for three-dimensional (3D) virtual models registered on the cranial base. (A–D) The registration of 3D surface models displayed with CMF software (Maurice Müller Institute, Bern, Switzerland) showing a color map of thousands of 3D surface distances that describe the soft tissue changes. (E) Registration of 3D renderings with Invivo software (Anatomage, San Jose, CA, USA) that allows visualization of the soft tissue changes with treatment.

the maxilla and the mandible from any perspective, and a highly detailed analysis of changes in the mandibular condyles can be visualized using color maps, so that all areas in the jaws or condyle that have changed from the previous CT scan are colored to distinguish both the direction of change and its amount (see Figure 6.1).¹

The superimposition methods presented in this chapter allow not only visualization, but also a precise localization of the skeletal remodeling/adaptation that has occurred in the maxilla or mandible. This approach to 3D image analysis methods has been streamlined and continuously updated with new methods for quantification with collaborations from the Maurice Müller Institute, Switzerland, the medical image analysis group in the UNC Department of Computer Science, the UNC Neuroimaging Laboratory, and the statistical modeling group in the UNC Biomedical Research Imaging Center.

The new emphases on soft tissues as the limiting factors in treatment and on soft tissue relationships in establishing the goals of treatment combine to produce major changes in diagnosis and treatment planning. This is a paradigm shift away from the previous emphasis on dental occlusion and hard tissue relationships, in which cephalometric analysis will play a smaller role and clinical examination of facial proportions a more important one. Clinical research is beginning to provide data from 3D soft tissue analysis, but the value added by 3D photographs still needs to be assessed in carefully controlled studies. Although the superimposition methodology presented here allows a quantification of soft tissue surface changes from any 3D dataset (Figure 6.10), its application to other imaging modalities such as laser scanners and 3D cameras has not yet been assessed.

CONCLUSION

The methodology presented has been applied to research currently in progress. The superimposition of 3D surface models is too time-consuming and computing-intensive for routine clinical use, but our current work has focused on making available a simplified analysis in the near future.

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Averaging Facial Images

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INTRODUCTION

Three-dimensional average faces find a number of applications in orthodontics and various craniofacial studies. These applications may include studying facial anomalies in comparison with normal facial morphology, evaluating average facial growth in a cohort of subjects, comparing facial morphologies for different ages, genders, and ethnicities, and so on.

The variation and change in the form and size of biologic objects are studied by the branch of bioinformatics called morphometrics. Traditional methods include measuring distances, angles, areas, and volumes.^{1,2} In the last three decades, more advanced methods have been developed based on the analysis of landmarks, points that have specific geometric locations, and associated biologic names. A morphometric study aims to describe a biologic shape in the simplest possible way, removing extraneous information and facilitating a comparison between different objects.^{3,4} The whole set of data describing the shape of an object is essentially replaced by a small number of landmarks, which are further analyzed by statistical methods. This approach uses the power of mathematics to study complex shapes in a rigorous fashion and permits their objective analysis rather than subjective assessment.

However, the techniques of morphometrics have some deficiencies. Most notably, nearly all quantitative data defining the shape are discarded, and just a small number of points are retained. For example, facial scans obtained with VI-900/910 laser cameras (Konica Minolta Sensing, Inc, Osaka, Japan) or 3dMD optical scanning devices are represented by approximately 50,000 datapoints, whereas only 20–40 landmarks are used to describe a face, and 60–80 landmarks are used in craniofacial studies.^{5,6,7} It is clear that most information about the shape is simply ignored. Furthermore, these landmarks may be difficult to identify, and there are individual dependent errors in placing landmarks, which are often higher than the data capture errors.

In this chapter, we outline techniques of averaging three-dimensional facial images defined by many thousands of datapoints that take into account all facial information available, with landmarks and methods of morphometrics also used at various stages.

PREREQUISITES OF AVERAGING

As is known from morphometrics, prior to comparing (or averaging) shapes, they need to be fitted into a frame of reference that places them in the same virtual space. This is achieved through the removal of translation, rotation, and size difference, as well as the superimposition of the shapes to make them appropriately aligned.^{3,4,8-11} In addition, the method of averaging is also important. Let us consider these in order.

Removal of translation

The necessity of removing translation can be illustrated as follows. For simplicity, consider two two-dimensional shapes that need to be averaged. Let the shapes be denoted by functions $f(x)$ and $g(x)$ defined on an interval $a \leq x \leq b$. If they are not translated relative to each other, their average, $h(x)$, is simply the arithmetic mean of them (Figure 7.1, left). If the shapes are translated (let $f_*(x)$ and $g_*(x)$ denote the respective translated versions), their average, $h_*(x)$ is different from the true average $h(x)$, as can be seen from Figure 7.1 (right). Moreover, the average $h_*(x)$ is defined on a shorter interval, which means that some information is lost.

Removal of rotation

Similarly, rotation of the shapes leads to distortion of the average and loss of information.

Removal of size difference

In morphometrics, the objects are usually scaled to the same relative size.¹⁰ This is relevant when relative size is of no interest and the focus is on relative shape differences. A scaling factor is then evaluated for each object based on the calculation of the so-called centroid size.^{3,4} However, facial size is an important

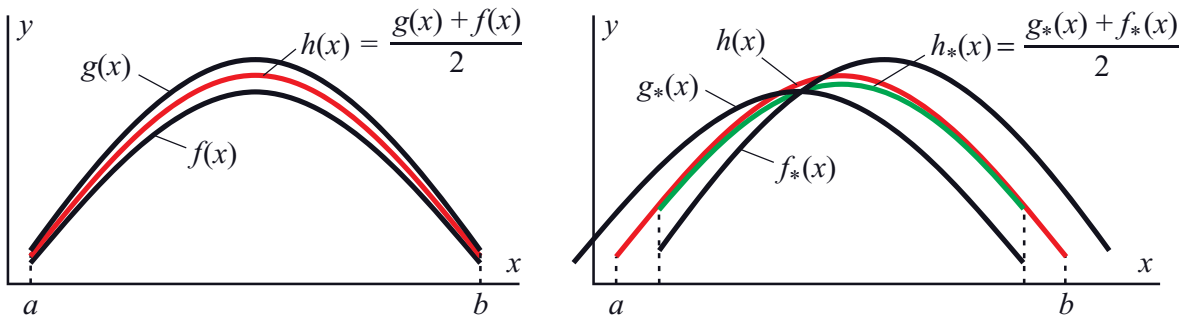


Figure 7.1 If two shapes, $f(x)$ and $g(x)$ (left), are translated relative to each other, $f_*(x)$ and $g_*(x)$ (right), their average, $h_*(x)$ (green line), will be different from the true average $h(x)$ (red line) and defined on a shorter interval.

factor in many clinical applications. Therefore, we choose not to discard the size factor in our averaging approach. Furthermore, using scaled or unscaled facial images will not affect our averaging techniques.

Superimposition

In morphometrics, the most common technique to superimpose shapes is to use the so-called Procrustes registration.^{3,4} Following this technique, all respective landmarks are superimposed so that the overall deviation between them is minimum, in the least squares sense. All four of the above steps combined are known as Procrustes analysis if there are two sets of landmarks to superimpose, or generalized Procrustes analysis (GPA) if there are many sets of landmarks.

Although powerful, Procrustes registration is not an ideal technique to superimpose numerous objects. This is because it relies only on landmarks and does not take into account other information available. This is especially true for facial scans, which are defined by thousands and tens of thousands of datapoints; these datapoints do not have fixed positions and hence cannot be used as landmarks. An alternative approach here is to use best-fit registration, where all the data are used to minimize the total deviation between shapes. However, this approach is not flawless. It works very well when all objects are sufficiently close in size overall and in the sizes of their individual features. In reality, this is not always the case, especially for facial images.

It would be ideal if each object had a single, easily identifiable central point (an origin) that did not change its relative position across the group of objects under study, and furthermore if it had a fixed set of three reference planes that preserved their mutual position from object to object. It would then be easy to superimpose all shapes on the origin so that the respective reference planes would coincide. This is, for example, the case for ideal geometric bodies having regular shape, such as rectangular parallelepipeds, cones, cylinders, or ellipsoids. Unfortunately, real biologic objects, human faces included, are quite irregular, and they do not have a fixed and easily identifiable origin and reference planes. However, in the next section we suggest an approach to finding such an origin and such reference planes for three-dimensional facial images.

Methods of averaging

Even when all objects have been appropriately superimposed, averaging them is still far from straightforward. The approach used in morphometrics based on the analysis of landmarks cannot be applied to constructing average shapes. Although it is easy to calculate the average positions of all landmarks, they are too few to restore the whole average shape.^{12,13}

To highlight problems occurring in choosing an averaging method, let us consider the following example. Suppose we have two aligned semi-circles as shown in Figure 7.2 and we want to construct their average. If we calculate the mean of two ordinates corresponding to each abscissa, we obtain the average shape shown in green; it is the so-called pointwise mean. One would expect that the resulting average shape would be a semi-circle of mean radius. As is apparent from Figure 7.2, the pointwise mean shape has the same width as the smaller semi-circle and furthermore is not a semi-circle (Figure 7.2, right).

So this example highlights the two major problems of pointwise averaging: the resulting mean shape is distorted, compared with the expected one, and some information is lost at the edges. This happened because we performed averaging in the vertical direction. To avoid both problems, averaging should be done in the radial direction from the common centre (Figure 7.3, left).

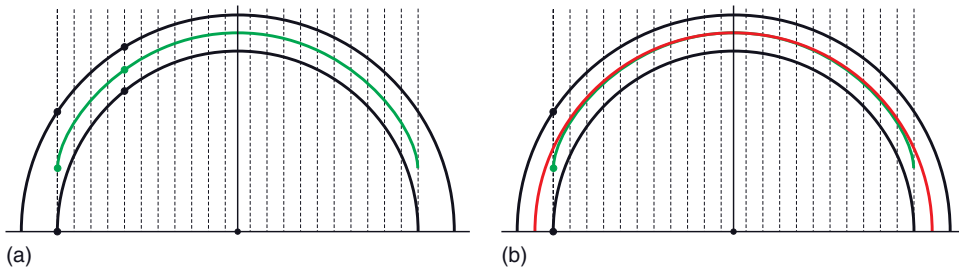


Figure 7.2 Pointwise averaging of two aligned semi-circles (black). The average shape (green) is obtained as the pointwise mean of the ordinates corresponding to each abscissa. The dashed lines indicate the averaging direction. The resulting pointwise mean shape is distorted compared with the true average (red) and lacks data at the edges.

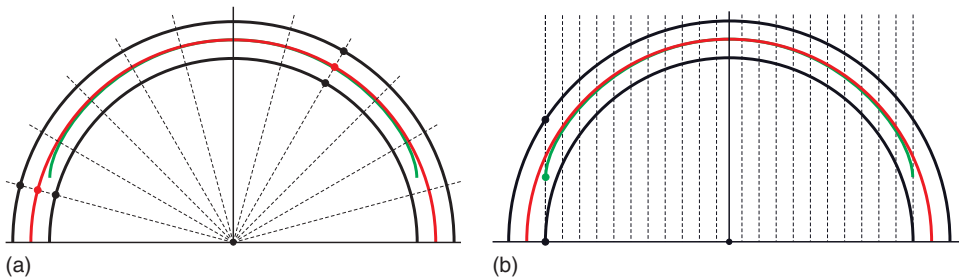


Figure 7.3 Radial (left) and normal (right) averaging of two aligned semi-circles (black). The average shapes (red) are obtained as the pointwise mean in the radial and normal direction. The dashed lines indicate the averaging direction. Both methods result in the true average.

The real shapes are not semi-circles, and they have neither a common origin nor a radial direction. It can be noticed from Figure 7.2 that the largest error and loss of information occurs where the lines along which the averaging is performed hit a shape at an acute angle; the smaller the angle, the greater the error. Where the averaging lines meet shapes at angles close to the right one or at least not too small, the error in determining the average shape and the loss of information are minimum.

For real biologic shapes, no method of averaging can provide zero error. However, as the above example shows, a good method should guarantee that the lines of averaging hit the shapes as perpendicularly as possible. Furthermore, choosing best possible origin and reference planes will keep the error of averaging at a minimum.

ORIGIN OF THE FACE

In order to develop an advanced superimposition technique for facial scans (shells), each represented by thousands of datapoints, we aim to find a most stable point (origin) and suggest a procedure for identifying reliable reference planes.

A successful candidate for the origin should be an easily identifiable point whose position changes least across a sufficiently large sample of images. To find such a point, a sample of 350 facial scans of

15½-year-old children, discussed in Chapter 13, was studied.^{5,6} Twenty-one reproducible landmarks were placed manually on each facial shell (see Figure 13.6). All faces were initially oriented to the approximate natural head posture,¹⁴ the right-to-left eye line giving the x -direction, the chin-to-forehead line giving the y -direction, and the nose pointing in the z -direction. The distribution of landmarks was studied using the following three methods:

- All facial shells were best-fit registered on a template (a randomly selected face from the sample), using Rapidform software (INUS Technology, Inc, Seoul, Korea), and translated so that the landmark centroid became the origin of coordinates, the point (0, 0, 0).
- All sets of landmarks were registered using GPA with scaling.
- All sets of landmarks were registered using GPA without scaling.

Preliminary knowledge indicates that the maxilla is subject to less change during facial growth than the mandible. Furthermore, the area around the eyes remains relatively stable, and the eye distance practically does not change significantly between 10 and 20 years of age.¹⁵ Therefore the most stable point, the point that shows statistically the least standard deviation across the whole sample, should be sought among the landmarks in the eye region. The standard deviations of all landmarks from their average positions were calculated in distance and each coordinate separately. The mid-endocanthion point (denoted “men”) was added to the set of landmarks. The results are listed in Table 7.1.

As seen in Table 7.1, the mid-endocanthion landmark shows the least standard deviation in all three methods, and it is therefore considered the most suitable candidate for the facial origin.

REFERENCE PLANES OF THE FACE

As in human anatomy, it seems reasonable to use the sagittal, coronal, and transverse planes as the reference planes for a facial shell.¹⁶ Below, we suggest a procedure for identifying these planes.

Sagittal plane

The sagittal (also known as mid-sagittal) plane is an imaginary plane that travels from the top to the bottom of the face and divides it into left and right portions. It is essentially a vertical symmetry plane. This description is not rigorous and gives us a lot of freedom in identifying the exact position of the sagittal plane.

All human faces are known to be asymmetric, and hence they do not have a symmetry plane. The landmarks that are supposed to lie on the midline (glabella, nasion, pronasale, subnasale, labiale superius, labiale inferius, and pogonion) do not in fact lie on a single line – deviations can be up to several millimeters for the pronasale and pogonion. Even all the 21 landmarks, considering that they should be approximately symmetric about the sagittal plane, cannot be used as reliable datapoints for identifying it. Landmarks account for just a tiny fraction of all available facial data. Furthermore, they are subject to human error in placing them. Their positions are defined to within 1–2 mm, whereas the accuracy of the scanned facial images is about 0.5 mm. Following the logic previously adopted, we want to use as much facial information as possible to be as precise as possible.

Table 7.1 Standard deviations (in mm) of all landmarks from their average positions in the x-, y-, and z-directions and the distance for the sample of 350 facial scans of 15-year-old children

		Best-fit registration (mm)				Generalized Procrustes analysis registration with scaling (mm)				Generalized Procrustes analysis registration without scaling (mm)			
Landmark		x	y	z	Distance	x	y	z	Distance	x	y	z	Distance
1	g	1.18	3.16	1.81	3.83	0.56	1.83	1.90	2.69	0.56	2.54	1.92	3.23
2	n	1.02	2.75	2.15	3.63	0.51	1.76	1.71	2.50	0.51	2.44	1.72	3.03
3	enL	1.62	2.77	2.69	4.18	1.33	1.07	1.47	2.25	1.42	1.73	1.66	2.78
4	enR	1.62	2.79	2.43	4.03	1.31	1.09	1.33	2.16	1.41	1.77	1.52	2.73
5	exL	2.23	3.10	3.07	4.90	2.11	1.48	1.49	2.98	2.06	1.85	1.81	3.31
6	exR	2.33	3.03	2.62	4.63	2.14	1.49	1.41	2.96	2.20	1.98	1.72	3.43
7	psL	1.90	3.06	2.39	4.32	1.60	1.35	1.45	2.54	1.62	1.92	1.61	2.98
8	psR	1.91	3.02	2.14	4.17	1.54	1.32	1.51	2.53	1.61	1.97	1.66	3.04
9	piL	1.81	2.94	2.75	4.41	1.64	1.26	1.45	2.53	1.63	1.79	1.65	2.93
10	piR	1.83	2.91	2.49	4.25	1.55	1.23	1.50	2.48	1.64	1.83	1.67	2.97
11	prn	1.12	3.17	3.33	4.73	0.91	2.06	2.30	3.22	0.90	2.06	2.63	3.46
12	sn	0.89	3.13	2.92	4.37	0.58	1.66	1.77	2.50	0.58	1.74	1.94	2.67
13	dlL	1.40	2.77	2.72	4.13	1.24	1.26	1.64	2.41	1.41	1.30	1.71	2.57
14	dlR	1.50	2.66	2.67	4.06	1.29	1.28	1.78	2.54	1.45	1.31	1.88	2.72
15	ls	1.12	3.42	2.65	4.48	0.45	1.13	1.27	1.75	0.45	1.78	1.57	2.41
16	li	1.30	4.50	2.58	5.35	0.45	1.84	1.58	2.46	0.45	2.97	1.67	3.44
17	cphL	1.32	3.36	2.54	4.42	0.89	1.09	1.10	1.79	0.93	1.65	1.37	2.34
18	cphR	1.36	3.30	2.52	4.37	0.89	1.06	1.13	1.79	0.89	1.62	1.44	2.35
19	chL	2.17	3.61	3.06	5.20	1.99	1.38	1.84	3.04	2.01	2.17	1.84	3.48
20	chR	2.33	3.67	2.71	5.12	2.10	1.36	1.77	3.06	2.17	2.21	1.78	3.57
21	pg	1.68	5.55	2.70	6.40	0.82	2.50	2.93	3.94	0.82	4.36	2.82	5.26
22	men	0.93	2.72	2.48	3.80	0.48	1.01	1.29	1.71	0.49	1.70	1.50	2.32

Three methods of registration were used: best-fit, general Procrustes analysis with scaling, and general Procrustes analysis without scaling. Among the landmarks in the eye region (1–10 and 22), the mid-endocanthion (men) shows the least standard deviations in all three cases; men values are given in bold to highlight the least-variation data and justify the selection of this point as the facial origin point.

The key to identifying a symmetry plane is using the mirror face.¹⁷ When the original facial shell and the mirror shell are registered together using the best-fit technique, the resulting structure becomes perfectly symmetric. We suggest that the symmetry plane of this structure should be treated as the sagittal plane for the original face.

Figure 7.4 illustrates a severe facial asymmetry, showing original face (a), mirror face (b), left–left (composed from the left part and its mirror reflection) face (c), and right–right face (d). Using facial landmarks to identify the sagittal plane turns out to be less effective. The symmetrization procedure described above proves to be effective even for highly asymmetric cases. Figure 7.5 illustrates the procedure of symmetrization and construction of the sagittal plane for the face shown in Figure 7.4.

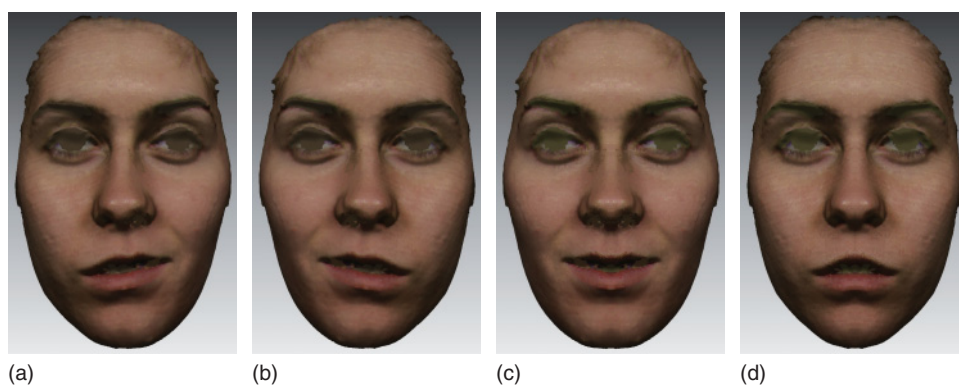


Figure 7.4 Facial asymmetry: (a) the original face, (b) the mirror face, (c) the left-left (composed from the left part and its mirror reflection) face, and (d) the right-right face.

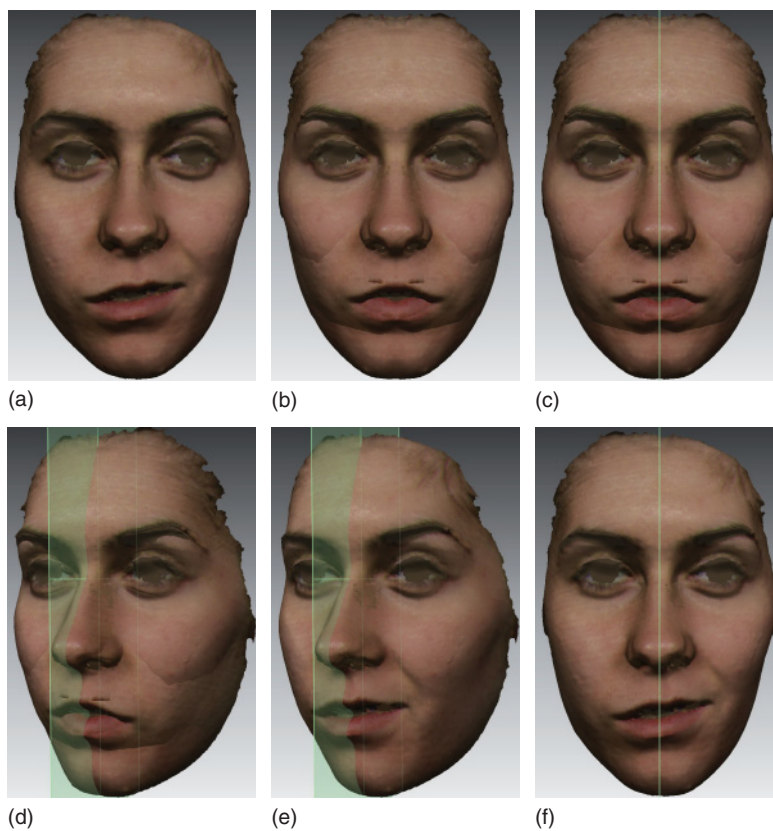


Figure 7.5 Symmetrization and construction of the sagittal plane: (a) original face, (b) symmetrized original-mirror face structure, (c) same with the sagittal plane, (d) same in an askew view, (e) same with the mirror face removed, and (f) same in frontal view.

Coronal and transverse planes

The identification of the coronal and transverse planes essentially requires the identification of the upright position, or natural head posture.¹⁴ However, if there is no such information (or it is inaccurate) from the time of scanning, we propose a procedure for determining these planes.

The main idea suggested here involves the construction of the cylinder that fits all facial datapoints for the symmetrized original-mirror face structure. There is no rigorous substantiation of this approach, but it seems from our experience that it is the most reliable method suggested so far. This method has been verified as being superior to ones based on landmarks only, and also to the technique relying on constructing the tensor of inertia of the symmetrized structure and computing the principal axes of the tensor.

The construction of the fitting cylinder essentially uniquely defines its axis. Knowing this axis, we can generate the transverse plane passing through the origin (mid-endocanthion). Furthermore, we can readily generate the coronal plane as the one perpendicular to both the sagittal and transverse planes and passing through the origin. What remains to be done is to translate the shell for mid-endocanthion to become the point with coordinates (0, 0, 0) and rotate the shell so that the xy -, yz -, and xz -plane are the transverse, sagittal, and coronal planes, respectively.

This procedure has been fully automated through a set of in-house VBA (Visual Basic Applications) subroutines for Rapidform; it requires only three landmarks to be set manually: left and right endocanthions (used to calculate the mid-endocanthion), and pogonion (used to identify the natural facial orientation). It should also be noted that the origin is in fact the projection of the mid-endocanthion on the sagittal plane, which means that it is effectively the middle point between the mid-endocanthion of the original shell and that of the mirror shell; by this, full symmetrization of the facial geometry is attained.

The main steps of this procedure are illustrated in Figure 7.6.

AVERAGING METHODS

It is now assumed that there are a number of facial shells resulting from pre-processing raw facial scans.¹⁶ The shells are assumed to have been fitted into the same frame of reference as described above: the origin is at the mid-endocanthion, the x -axis is perpendicular to the sagittal plane and directed from the right eye to the left eye, the y -axis is perpendicular to the transverse plane and points vertically upward from chin to forehead, and the z -axis is perpendicular to the coronal plane and points in the nose direction.

We now focus on methods of averaging and consider the following four methods:

- straightforward pointwise averaging in the z -direction;
- averaging in the radial direction of the average facial cylinder;
- averaging in the radial direction of the average facial sphere;
- averaging in the locally normal direction to a template shell.

All these methods have been implemented as in-house VBA subroutines for Rapidform. Below are brief descriptions of the methods, followed by a discussion of their advantages and disadvantages, and illustrated by some examples.

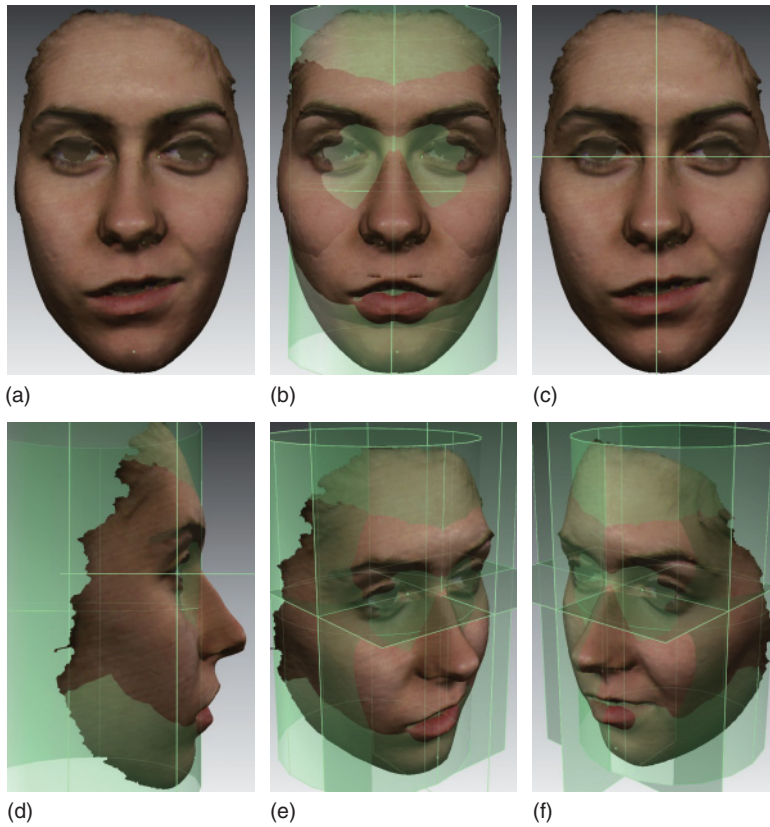


Figure 7.6 Identifying natural head posture and reference planes: (a) original face with three landmarks, (b) original-mirror face structure with the facial cylinder, (c) original face with the three reference planes, (d) original face with the cylinder and the coronal and transverse planes (lateral view), (e) original face with the cylinder and all reference planes (right askew view), and (f) same in left askew view.

Averaging in the z-direction

This averaging procedure may be outlined mathematically as follows.¹⁸ Suppose there are K facial shells appropriately as described above; all of them are bounded within a box $\{x_{\min} \leq x \leq x_{\max}, y_{\min} \leq y \leq y_{\max}, z_{\min} \leq z \leq z_{\max}\}$. Each face is considered to be a function $z = f_k(x, y)$, where k represents the number of the face. The functions f_k are evaluated at nodes (i, j) of a uniform rectangular mesh, so that:

$$\begin{aligned} z_{ij}^k &= f_k(x_i, y_j), \quad k = 1, \dots, K, \quad i = 0, \dots, M, \quad j = 0, \dots, N; \\ x_i &= x_{\min} + i\Delta x, \quad \Delta x = \frac{x_{\max} - x_{\min}}{M}, \quad x_0 = x_{\min}, \quad x_M = x_{\max}; \\ y_j &= y_{\min} + j\Delta y, \quad \Delta y = \frac{y_{\max} - y_{\min}}{N}, \quad y_0 = y_{\min}, \quad y_N = y_{\max}. \end{aligned}$$

The averaging is performed along the z -axis (Figure 7.7) so that the z -coordinates of the average face are calculated pointwise as the arithmetic mean of all respective z -coordinates of the K faces:

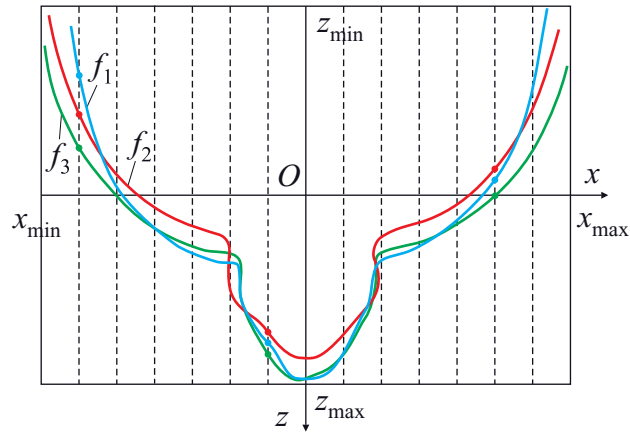


Figure 7.7 Pointwise averaging in the z -coordinate; point O is the origin of the reference frame (mid-endocanthion).

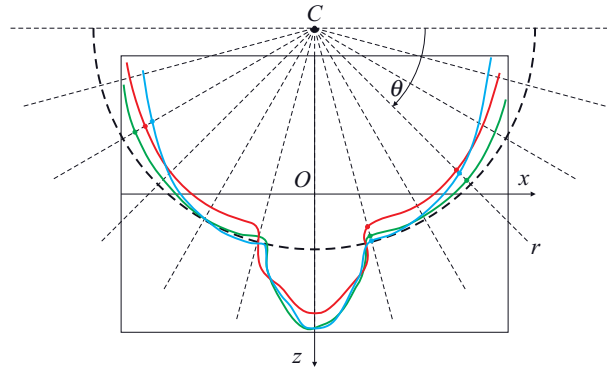


Figure 7.8 Pointwise averaging in the radial direction of the cylindrical coordinate system.

$$z_{ij}^{\text{ave}} = \frac{z_{ij}^1 + \dots + z_{ij}^K}{K}.$$

The average face is thus defined by the point cloud $\{x_i, y_j, z_{ij}^{\text{ave}}\}$. The point cloud is then triangulated to obtain an average facial shell, which is further improved by removing possible mesh defects and by filling in small holes.

Averaging in the cylindrical radial direction

This method is similar to the previous one with the exception that cylindrical coordinates r, θ, y are introduced instead of the Cartesian x, y, z and the averaging is performed in the radial coordinate r (Figure 7.8). The axis of the cylindrical coordinate system is parallel to the y -axis, and its position is

defined as follows. The cylinder that fits all facial datapoints is constructed for each face. Then the average cylinder is calculated. The position of its axis is taken to be that of the cylindrical coordinate system.

The main formulae for this method are as follows:

$$r_{ij}^{\text{ave}} = \frac{r_{ij}^1 + \dots + r_{ij}^K}{K}, \quad r_{ij}^k = g_k(\theta_i, y_j), \quad x = r \cos \theta + c_X, \quad z = r \sin \theta + c_Z,$$

with $(c_X, 0, c_Z)$ being the coordinates of the point, C , at which the axis of the average cylinder intersects the transverse plane. The average face is defined by the point cloud $\{r_{ij}^{\text{ave}} \cos \theta_i + c_X, y_j, r_{ij}^{\text{ave}} \sin \theta_i + c_Z\}$.

Averaging in the spherical radial direction

This method uses spherical coordinates r, φ, ψ , and the averaging is performed in the radial coordinate r . The origin of the spherical coordinate system is taken to be the average centre of the spheres that are constructed for each face to fit all facial datapoints. The main formulae for the method are the following:

$$r_{ij}^{\text{ave}} = \frac{r_{ij}^1 + \dots + r_{ij}^K}{K}, \quad r_{ij}^k = h_k(\varphi_i, \psi_j),$$

$$x = r \cos \varphi \sin \psi + S_X, \quad y = r \sin \varphi \sin \psi + S_Y, \quad z = r \cos \psi + S_Z,$$

with (S_X, S_Y, S_Z) being the coordinates of the centre of the average sphere. The average face is defined by the point cloud $\{r_{ij}^{\text{ave}} \cos \varphi_i \sin \psi_j + S_X, r_{ij}^{\text{ave}} \sin \varphi_i \sin \psi_j + S_Y, r_{ij}^{\text{ave}} \cos \psi_i + S_Z\}$.

Normal averaging using a template

Suppose there is a surface, which we call a template, defined by a discrete set of points $\{\mathbf{r}_i\}$ with coordinates $\mathbf{r}_i = (x_i, y_i, z_i)$. Let $\mathbf{n}_i$ denote a unit normal vector to the surface at the point $\mathbf{r}_i$, and let d_i^k denote the signed distance from $\mathbf{r}_i$ to the facial shell k along the normal $\mathbf{n}_i$. This surface can be used to compute an average face according to the formula:

$$\mathbf{r}_i^{\text{ave}} = \mathbf{r}_i + \frac{d_i^1 + \dots + d_i^K}{K} \mathbf{n}_i$$

The question arises: How should one choose a template that would provide a higher accuracy of averaging than the above three methods? In view of our previous remarks, it is clear that the highest accuracy is achieved if the line along which the averaging is performed meets the facial shell at the right angle. It is also clear that a single line cannot meet all the shells (that need to be averaged) at the right angles. But we can try to provide that all these angles are close to the right angle “on average”; in this case, our target will be reached and the accuracy of averaging will be highest.

The ideal candidate for a template possessing this property would be the average face. But it is the average face that we look for, and to construct it we need to know the average face. This vicious circle leads us to the idea of organizing the following iterative procedure. At the first step, we calculate an average shell using one of the above three methods. We then use this shell as the template and calculate another average, which can further be used as the template for the next step, and so on. This procedure can be continued until the desired accuracy is attained, that is, when the average shell obtained at the current step becomes practically indistinguishable from that obtained at the previous step (Figure 7.9).

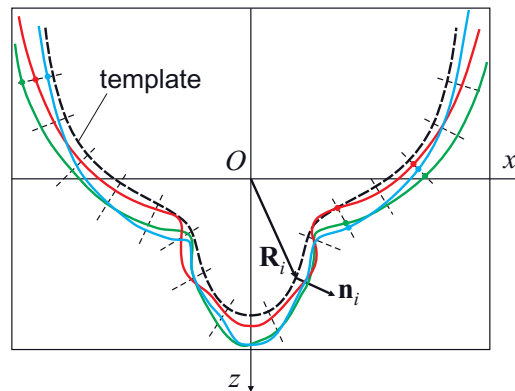


Figure 7.9 Pointwise averaging in the local normal direction at each point of a template.

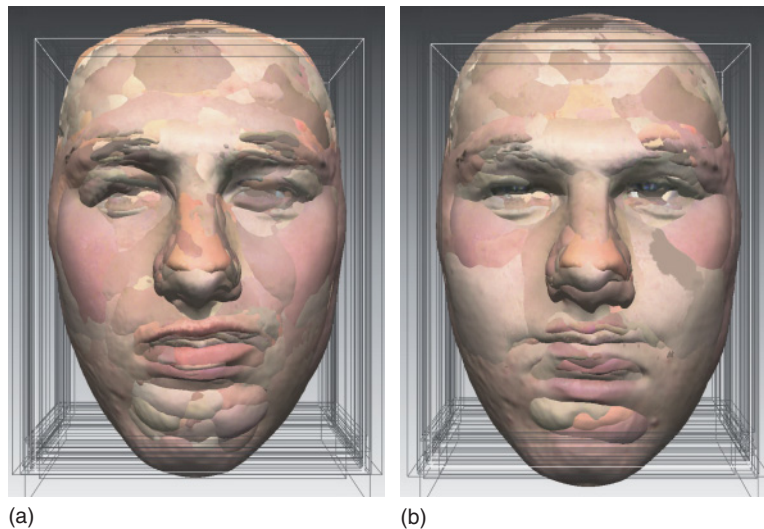


Figure 7.10 Thirty 15-year-old male faces superimposed using the best-fit (a) and reference-frame (b) techniques.

COMPARISON OF THE AVERAGING METHODS

To illustrate and compare the above methods, we considered a random sample of 30 male faces from the group of 350 faces of 15½-year-old children mentioned above. These faces were aligned on the common frame of reference as described above.

Best-fit versus reference-frame superimposition

We first compared the effect of superimposition on the average face. Two techniques were examined: best-fit and reference-frame. Figure 7.10 shows 30 faces superimposed using these two techniques. As

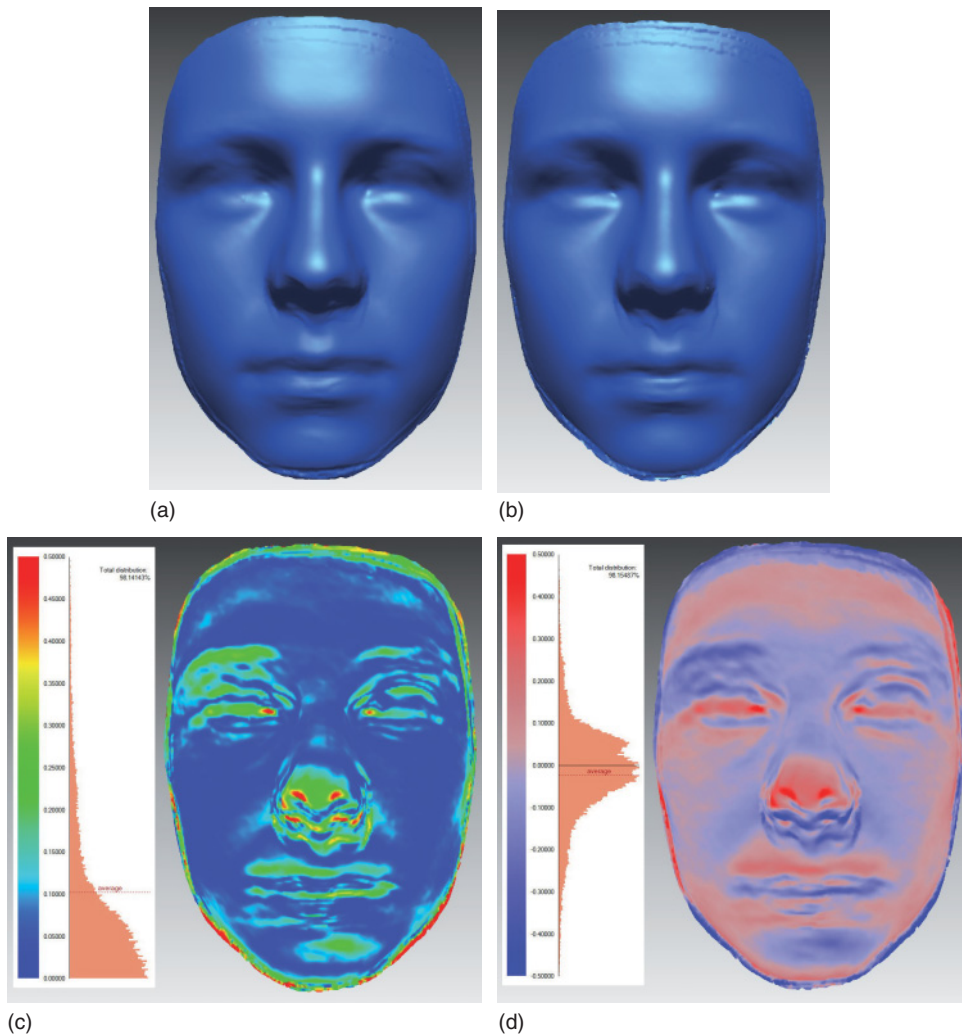


Figure 7.11 Comparison of the average faces obtained by averaging 30 facial shells in the z-coordinate, superimposed using the best-fit (a) and reference-frame (b) techniques. Color deviation maps are shown for the two averages in absolute color (c; range from 0 to 0.5 mm) and signed color (d; range from -0.5 to 0.5 mm); shades of red on the signed color map highlight the areas where the best-fit average is in front of the reference-frame average.

one should expect, the reference-frame registration technique provides a clearer and sharper picture in the eye region.

Figure 7.11 displays the resulting average faces obtained using averaging in the z-coordinate. Again, a noticeably sharper picture is seen in the eye region for the reference-frame registration (Figure 7.11b). The absolute (Figure 7.11c) and signed (Figure 7.11d) color deviation maps show the systematic error distribution due to the superimposition technique. In the eye, nose, lip, and chin regions, this error amounts to 0.2–0.5 mm. Note that the scanning and image-processing error effectively vanishes after averaging.

The defects appearing near the edges of the average faces are due to a lack of information in these regions (some faces being considerably larger than others). The wrinkles around the nose and lips are

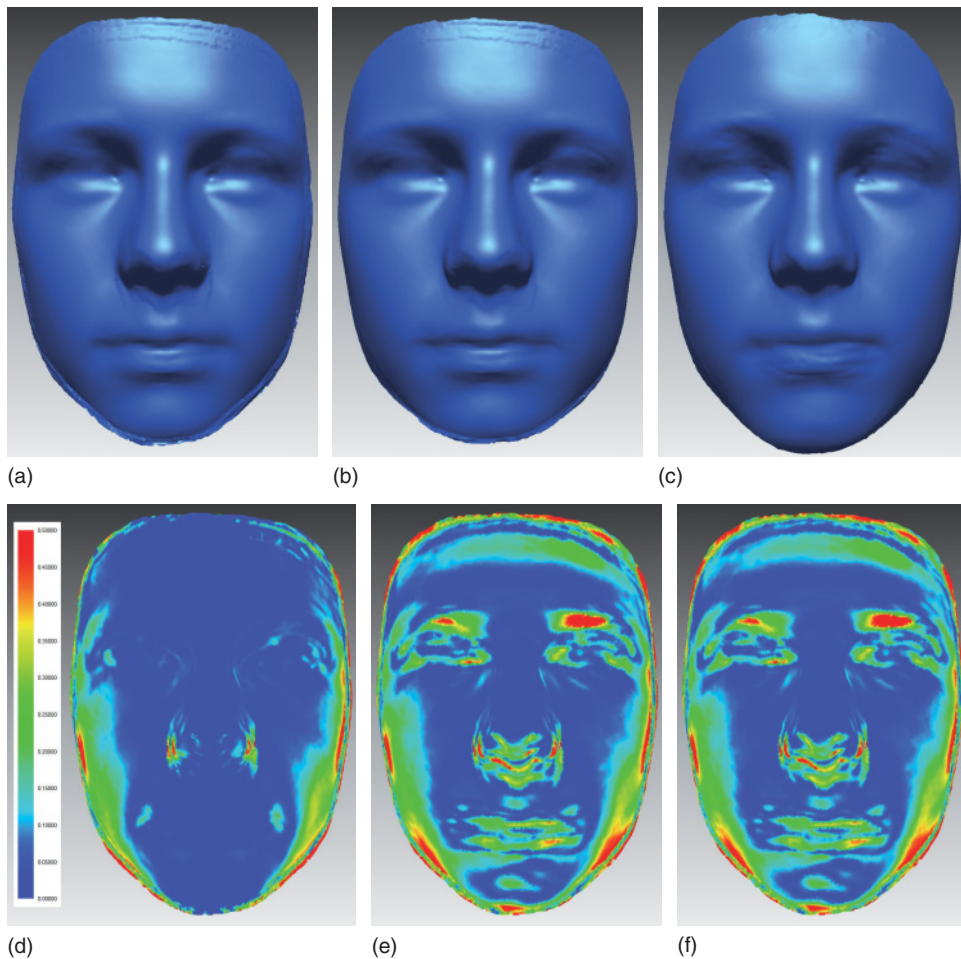


Figure 7.12 The faces obtained by averaging 30 reference-frame superimposed images using three different methods: z-coordinate (a), cylindrical radial (b), and spherical radial (c). Absolute-color deviation maps give pairwise comparison of the averages obtained by the three methods: z-coordinate versus cylindrical radial (d), z-coordinate versus spherical radial (e), and cylindrical radial versus spherical radial (f); the range of deviations is from 0 to 0.5mm.

due to differences in facial size and the fact that too few images are averaged. All these defects tend to smooth out as the number of faces used for averaging increases.

Averaging in the z-coordinate and cylindrical and spherical radial directions

Figure 7.12 displays three average faces (Figure 7.12a–c) obtained for the 30 male faces superimposed using the reference-frame technique by averaging in the z-coordinate (z-average), in the cylindrical radial direction (CR-average), and in the spherical radial direction (SR-average). The bottom row of images in

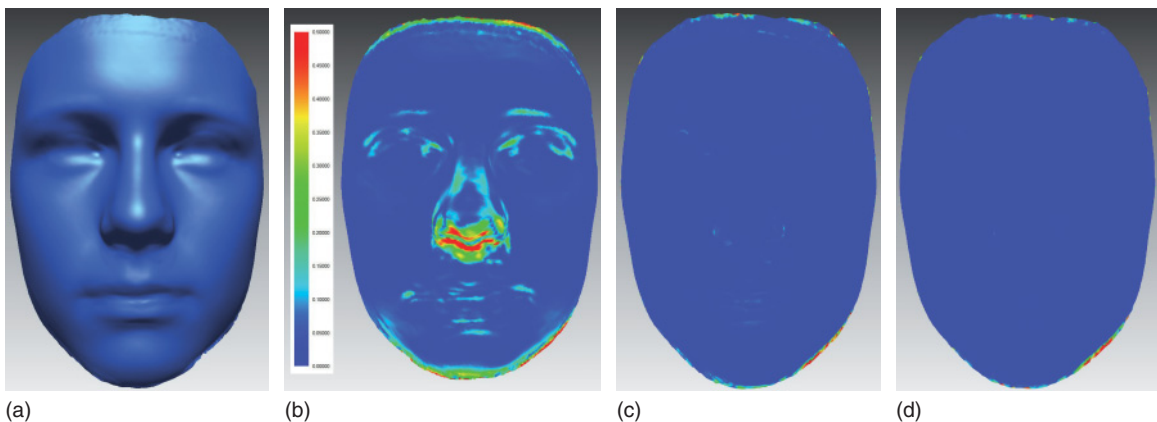


Figure 7.13 The face obtained by averaging 30 reference-frame superimposed images using the iterative template averaging method after three iterations (a). The absolute-color deviation maps show pairwise differences between the initial, obtained by cylindrical radial averaging, and first-iteration averages (b), first- and second-iteration averages (c), and second- and third-iteration averages (d); the range of deviations is from 0 to 0.5 mm.

Figure 7.12 compares the three averages, showing color maps of the deviation between them: z versus CR (Figure 7.12d), z versus SR (Figure 7.12e), and CR versus SR (Figure 7.12f).

As one would expect, the z-average contains noticeable errors (0.2–0.5 mm) at the edges of the face and on the sides of the nose, where the lines of averaging meet faces at too small an angle. Comparison of the CR- and SR-averages shows that they match each other very well in the central region but have considerable discrepancies at the bottom and top, as well as in the lip, nose, and eye regions – this is where the lines of averaging meet faces at significantly different angles.

Template averaging

As suggested in the previous section, iterative averaging on a template (T-averaging) should be performed to achieve the best possible results. To demonstrate this, we have carried out three iterations using the CR-average as the initial template and the resulting T-averages as the template for the next iteration.

The average face obtained after three iterations (T3-average) is displayed in Figure 7.13a. By visually comparing it with the previous averages, one can see that all facial features have become cleaner and sharper. Furthermore, the images in Figure 7.13b–d show deviation maps between the current and previous average for each three iterations: T1 versus CR, T2 versus T1, and T3 versus T2. As one can easily see, the second-iteration average (T2) shows practically no difference from the first-iteration average (T1). The respective average distances and their standard deviations for the three iterations are as follows: 0.040 and 0.077 mm (T1 versus CR), 0.005 and 0.026 mm (T2 versus T1), and 0.002 and 0.019 mm (T3 versus T2).

The third-iteration average may be treated as the “true” average for the selected method of superimposition. It is further used to assess the other methods of averaging. Figure 7.14 shows deviation maps between the z and T3 (Figure 7.14a), CR and T3 (Figure 7.14b), and SR and T3 (Figure 7.14c) averages. It is apparent that all the first three methods of averaging have artifacts commensurable to those of the

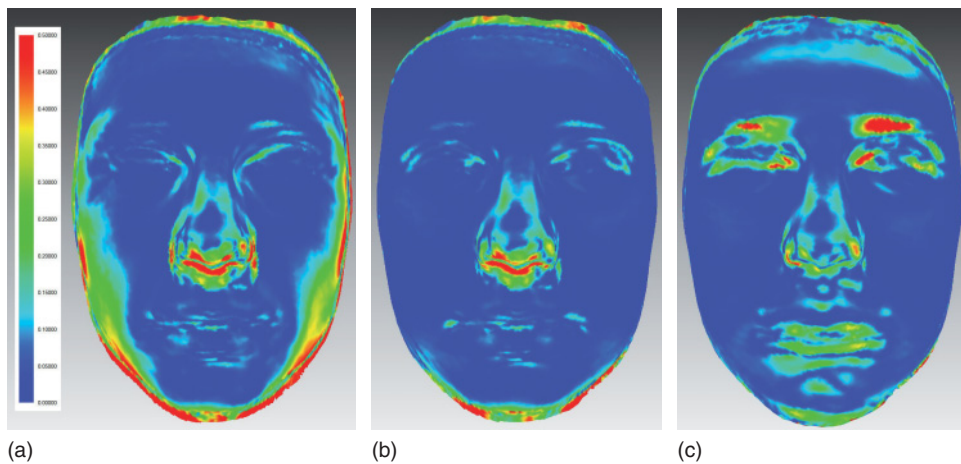


Figure 7.14 Comparison of the average faces obtained by the z-coordinate, cylindrical radial, and spherical radial averaging methods versus the one obtained by the iterative template averaging method. Absolute-color deviation maps show respective differences (a–c); the range of deviations is from 0 to 0.5 mm.

superimposition technique. Therefore, it can be concluded that the method of superimposition does not have a significant effect on the average face where the z-, CR-, or SR-averaging method is used, because all of them have approximately the same level of error. It is only important if the average is constructed using the iterative template method with two or three iterations.

Among themselves, the three methods can be ranked, in order of decreasing accuracy, as follows: cylindrical radial, spherical radial, and z-coordinate averaging method. It seems that the human face is better approximated by a cylinder than a sphere or a plane.

DISCUSSION

The techniques of geometric morphometrics are based on a massive simplification of biologic forms by representing them as sets of landmarks.^{3,4,7,9,10,12,13,19} The comparison of actual forms is thus reduced to the comparison of these sets of landmarks; typically, only a few tens of landmarks are used. This approach allows an effective and rigorous analysis of the forms and their main features associated with the landmarks.

However, modern equipment permits capturing the shapes of biologic objects with high resolution, generating from tens to hundreds of thousands of datapoints. These points do not usually have biologically fixed positions and cannot be regarded as landmarks; they therefore cannot be treated using the morphometrics methods. Landmark-based studies take into account just a tiny fraction of the data available, discarding most of the information and not realizing the potential of the modern scanning devices. Today's clinical applications require that one takes into account as much available information as possible to achieve higher accuracy. Advanced methods of morphometrics need to be developed to meet the growing demand for an increased accuracy of analysis.

Prior to comparing biologic objects, they need to be fitted into a frame of reference that places them in the same virtual space. This is achieved by Procrustes registration of landmark sets through the removal

of translation, rotation, and size differences, followed by an appropriate superimposition that minimizes the overall deviations between the landmarks sets.^{3,4} (However, removing size differences is not performed if size is as important as shape.) Already at this stage, some improvements can be made by taking into account all the available data on the objects as well as their specific features.

Our further discussion relates to human faces, each represented by a triangulated mesh of datapoints, which is called a facial shell. One approach to registering such shells is to use a best-fit technique,^{5,6,14,18,20–21} where the overall deviation between shells across the whole surface is minimum, in the least squares sense. This approach takes into account all or nearly all available surface data. It provides best results in the cases where the shells and their individual features have close dimensions.

The best-fit registration algorithm is a standard tool efficiently implemented in many commercial software packages, such as Rapidform, Geomagic (Geomagic, Inc, Research Triangle Park, NC, USA), PET (Konica Minolta Sensing, Inc), and so on. However, this algorithm is computationally expensive and memory-consuming, especially in cases where hundreds of shells need to be simultaneously registered (groupwise registration). Furthermore, the algorithm may become unstable if the shells are not appropriately aligned. To avoid these problems, each shell is registered on one and the same template (pairwise registration), a randomly selected shell from the group of images under study. It should also be noted that the quality of pairwise registration may be considerably worse than that of groupwise registration.

An alternative approach to registering facial shells, suggested in this chapter, is to introduce a common frame of reference including a common origin and three reference planes. The mid-endocanthion is suggested as a good candidate for the origin; this appears to be the most stable point among the facial landmarks. An algorithm for the identification of the reference planes (sagittal, transverse, and coronal) is suggested based on using the mirror face and the cylinder that fits all datapoints of the original–mirror face structure. The technique is mathematically robust and individual-independent.

Advancements can also be made at the stage of the analysis of objects. An important way of analyzing and comparing facial shells is constructing an average face. Although it is easy to calculate the average positions of respective landmarks for a given group objects, these landmarks are too few to restore the whole average shell. Some improvement can be achieved by introducing more landmarks and generating a network of curves determined by them. The average face may then be represented as an averaged network of curves. Still, this approach ignores most of the data available and is very difficult to automate.

Four methods of averaging faces have been considered here. Three new algorithms (averaging in the cylindrical radial direction, spherical radial direction, and local normal direction to a template) are suggested and compared with the old algorithm of averaging in the z-coordinate (the direction where the face looks).¹⁴ The best result is achieved by iterative averaging in the local normal direction to a template, ensuring that the line of averaging meets all faces at nearly right angles, thus providing maximum accuracy (see Figures 7.13 and 7.14). The resulting average face at the current step is taken to be the template at the next step. The procedure converges rapidly to the “true” average face; two or three iterations suffice to attain an accuracy of averaging of several microns. When all facial shells are superimposed using the reference-frame technique, with the mid-endocanthion being the origin, the resulting average face is very sharp in the eye region. Tiny wrinkles are noticeable in the nose and lip regions; these are due to size differences in the faces. However, these wrinkles will smooth out with increasing the number of facial shells.

If only the average face shape is important and the size differences need to be excluded, each shell should be scaled appropriately. We suggest that the scaling factors should be calculated based on the first principal component (mostly accounted for by face height) computed from the landmark data using principal component analysis (see Chapter 13). The scaling factors obtained by GPA are less suitable, since they rely on an evaluation of the so-called centroid size, which is based on computing the squared

distances from landmarks to their centroid. This approach has the drawback that all landmarks are treated as equally important, which is not the case since they are not uniformly distributed across the face. Moreover, the errors in identifying landmarks are all different.

For studies analyzing individual features, such as the lips or the nose, it can be suggested that the facial shells should be superimposed in such a way that the respective landmark centroids are taken as the origin of the coordinate system, with the reference planes identified in the same way as previously described.

It should also be noted that the real accuracy of facial shells obtained with Konica Minolta 900/910 scanners is about 0.3–0.5 mm (images obtained with latest 3dMD [Atlanta, Georgia, USA] cameras are accurate to 0.8–1.0 mm).²¹ The errors due to the superimposition technique are about 0.2–0.5 mm (see Figure 7.11) and the errors associated with the first three methods of averaging are again 0.2–0.5 mm (see Figure 7.12). The last method hardly brings any error at all; it can be evaluated to be less than 0.1 mm for 20–30 facial shells and effectively vanishes with increasing the number of shells. Therefore, it is essential to choose the right methods of superimposition and averaging in order to ensure the minimum error in the average face.

CONCLUSION

Modern three-dimensional surface scanning devices provide a high accuracy of measurement of under 1 mm and generate many thousands of datapoints. This opens up new perspectives for various orthodontic and craniofacial studies and applications. The traditional, landmark-based methods of geometric morphometrics fail to take full advantage of the new possibilities. Advanced methods of morphometrics employing all the information available need to be developed.

We have suggested advanced techniques for constructing average three-dimensional facial images. Although using landmarks, these techniques are essentially based on all datapoints of the scans and include, first, the registration of facial shells using a common reference frame, and second, iterative averaging in the locally normal direction to a template. The registration of three-dimensional objects is the key point in their further analysis. It involves finding a common origin and common reference planes, followed by removing translation and rotation to superimpose the objects on the common reference frame.

With a sample of 350 faces, we have found that mid-endocanthion is the statistically most stable point and is therefore most suitable as the common origin. An automatic procedure has been suggested to identify the reference planes (sagittal, transverse, and coronal) based on using the mirror face, best fit registered with the original face, and the cylinder that fits all datapoints of the symmetric original–mirror face structure. This procedure is superior to the traditional, landmark-based Procrustes registration for two reasons: first, it uses the most stable point of the face rather than the landmark centroid, and second, it uses reference planes defined by all datapoints rather than by only a small number of landmarks.

The facial average is obtained by calculating pointwise mean coordinates for all shells along a certain direction. The best accuracy is achieved when a mean is calculated in the direction locally perpendicular or nearly perpendicular to all shells. This approach is implemented by using a template shell and calculating means in the locally normal direction to the template; the resulting average shell is further used as a new template, and the averaging is repeated. This iterative procedure rapidly converges, and two or three iterations normally suffice for practical purposes.

The above registration and averaging methods are implemented as a set of in-house VBA subroutines for Rapidform.

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Part 2

Applications, Physiological Development, and Surgical Procedures

8

Studying Facial Morphologies in Different Populations

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INTRODUCTION

Three-dimensional (3D) imaging of the facial region and its supporting structures has become very popular over the last 20 years.¹⁻³ Traditional two-dimensional (2D) modes for record-taking have been replaced by 3D entities and are being used to diagnose orthodontic malocclusions. Although frontal and lateral cephalometric radiographs, panoramic radiographs, and intra- and extra-oral photographs are still used, more emphasis has been placed on the 3D virtual outlook^{4,5} and soft tissue esthetics.⁶ In the past, study models have probably been the leading “3D” records routinely used by practicing orthodontists and have given clinicians the ability to examine malocclusions from many viewpoints. Current virtual technologies have certainly enhanced the digitization of 3D models and have added value to the clinician.⁷

The paradigm shift in treatment philosophies also means that many clinicians have started to plan from the external profile, placing importance on the soft tissues of the face as they largely determine the limitations of orthodontic treatment. From the perspectives of function, stability, and esthetics, the orthodontist must plan treatment within the patient’s limits of soft tissue adaptation and soft tissue contours.⁸ With the developments in technology, many clinicians have shifted towards digital computer-based records for quicker results, easier organization, the ability to enlarge and enhance images, and ease of sharing this information with patients and colleagues.

3D images of the facial soft tissue can help provide the clinician with this same degree of information with a more accurate representation of facial morphologies⁹⁻¹¹ and can be useful to better understand, compare,^{3,12} and predict treatment outcomes before and after orthodontic treatment.¹³⁻¹⁵ In addition, some 3D soft tissue models have been used to estimate growth changes.^{16,17}

Some of the applications of 3D imaging in orthodontics include pre- and post-orthodontic assessment of dentoskeletal relationships and facial esthetics, auditing orthodontic outcomes with regard to soft and

hard tissues, 3D treatment planning, and 3D soft and hard tissue prediction. 3D-fabricated custom-made arch wires and archiving 3D facial, skeletal, and dental records for in-treatment planning, research, and other medicolegal purposes are some other benefits of using 3D models in orthodontics.¹⁸

This chapter reviews the use of 3D imaging in the study of the facial morphologies of subjects from different populations.

THE STUDY

We have known for some time that faces are different, especially when ethnic populations are involved. This is best illustrated using surface shapes and volumes from different populations. In this chapter, five different populations are discussed. Subjects were recruited from five sites in five different countries (Hungary [Hun], United Kingdom (Wales) [Wel], United States of America (Houston, Texas) [Hou], Slovenia [Slo], and Egypt [Egy]). All subjects were invited to participate in the study if they met the following inclusion criteria:

- ethnic descent/native of their country or state;
- between the ages of 18 and 30 years old;
- normal Class I malocclusions with no adverse skeletal deviations;
- normal body mass index values;
- no gross craniofacial anomalies.

Imaging systems

Two main imaging systems, the Minolta VI-900 (laser scanning) and 3dMDface (stereo-photogrammetric) systems (Konica Minolta, Tokyo, Japan), were used in this study.

The laser scanning system consisted of two high-resolution Minolta VIVID VI-900 3D cameras, with a reported manufacturing accuracy of 0.1 mm, operating as a stereo-pair. Each camera emits an eye-safe Class I laser, 690 nm at 30 mW, with an object-to-scanner distance of 600–2500 mm (depending on the lens type) and a fast mode scan time of 0.3 seconds. The system uses a one-half-frame transfer charge-coupled device and can acquire 307,000 datapoints. The scanner's output data is 640 × 480 pixels for 3D and red, green, and blue color data. Data were recorded on a desktop workstation, and for surface capture a Minolta medium-range lens with a focal length of 14.5 mm was used. The cameras were placed 1350 mm from the subjects. The scanners were controlled with multiscan software (Cebas Computer, GmbH, Eppelheim, Germany), and data coordinates were saved in a software file format known as a VIVID file format (.vvd). The system has previously been validated.^{19,20}

The 3dMDface system is a structured light system using a combination of stereo-photogrammetry (a technique used to acquire 3D objects from stereoscopic images) and the structured light technique, and was also a portable system.¹³ This system uses a multicamera configuration, with three cameras (one color and two infrared) on each side that capture photorealistic-quality pictures. A random light pattern is projected onto a subject, and an image is captured with multiple synchronized digital cameras set at various angles in an optimum configuration. This system is able to capture full facial images from ear to ear and under the chin in 1.5 milliseconds at the highest resolution. The manufacturer's accuracy is <0.5 mm, and the quoted clinical accuracy is 1.5% of the total observed variance.²¹ 3D surface images captured by surface acquisition systems are highly repeatable, and 3D landmark data can be acquired with a high degree of precision.^{2,22}

Image acquisition

In order to produce an accurate facial structure, natural head posture was adopted for all subjects, as this has been proven to be clinically reproducible.²³ The subjects sat on an adjustable chair and were asked to look into a mirror with a horizontal and vertical line marked on it. They were asked to level their eyes to the horizontal line and to adjust the midline of their faces to line up with the vertical line. Adjustments to seating heights were made to assist the subjects in achieving natural head posture. The subjects were asked to swallow hard and to keep their jaws in a relaxed position just before the images were taken. Each image acquisition took 1.5 milliseconds.

Processing of facial shells

Completed 3D facial images were then imported into a reverse modeling software program (Rapidform 2006, or RF6; INUS Technology, Inc, Seoul, South Korea) for analysis. Together, these functions allowed high-quality polygon meshes, accurate freeform nonuniform rational B-spline surfaces, and geometrically perfect solid models to be created. RF6 generated data as absolute mean shell deviations, standard deviations of errors during shell-to-shell overlaps, maximum and minimum range maps, histogram plots, and color maps.

The initial file formats imported into RF6 had a semi-rough image texture due to the irregularity of the surface contours and the way in which light was reflected off the surfaces of different objects. Further data-processing by a custom-built software subroutine to produce a workable image that preserved the shape, surface, and volume.²⁴ The images were checked individually, and unwanted areas that could not be automatically removed were removed manually by dividing the unwanted areas from the main shell before proceeding to the next stage. Surface meshes with “defects” or “holes” were filled-in automatically by RF6. Finally, one composite whole face per individual subject was generated.

Average face constructions

Average faces were constructed in this study to represent the average, and their variations were based on the facial morphology of different study populations. The average facial constructs were achieved by using a previously validated software subroutine created from tools available within RF6. The steps required to produce an average face have been discussed previously²⁵ in this book.

Parameters measured

Ten average male and female facial shells from each population were created and established. Each gender-specific average face was superimposed onto a population-specific gender template, using a specialized superimposition technique²⁶ to compare morphologic differences between each one. This was done until all possible combinations were achieved. The method of superimposition utilized a systematic process and involved manually aligning five points of the facial scans (2 points on the inner canthus of the eyes, 2 points on the outer commissure of the lips, and 1 point on the nasal tip) and subsequently fine registration in which the computer software RF6 determined the best-fit of the two scans.

The following areas were analyzed:

- linear measurements
- color histograms
- surface areas/shapes.

Linear measurements

Linear measurements representing the mean differences between two surface shells were measured and recorded in millimeters. This value represents the sum total of all differences recorded between the overlapping surfaces of two shells, and the value could be used as an indicator of the best-fit between two shells. In addition, these values showed the changes in surface fit or regions of changes on the full faces.

Color histograms

Color deviation maps, as previously mentioned, were produced using the software tool RF6 PP2. The color maps gave an indication of the areas of change that occurred between the average facial shells. In this study, blue areas showed “negative” changes and red areas showed “positive” changes.

Surface areas/shapes

Surface areas and shapes were automatically generated by RF6. These shapes were obtained when a previous tolerance of 0.425mm was applied to the paired surface shells studies. The areas that corresponded to 0.425mm were deemed to be similar surfaces, whereas surface areas above this tolerance showed up as surface shapes and color deviations. These methods are described in Figure 8.1.

UNDERSTANDING THE RESULTS

Sample size

In this chapter, the final sample was made up of 473 subjects that consisted of 244 males and 229 females. The mean ages for the male and female subjects were 23.5 years and 25.2 years, respectively.

Measurements

The surface shells for each average subgrouping were superimposed onto one another using a previously denoted superimposition technique.²² A total of 10 different pairs were established for each male and female set. The results of the study are presented as follows.

Linear measurements

Distinct differences in the absolute linear measurements between surface shells were noted in the different gender-specific subgroupings. The linear differences ranged from 0.37mm (Wel_Slo) to 1.00mm

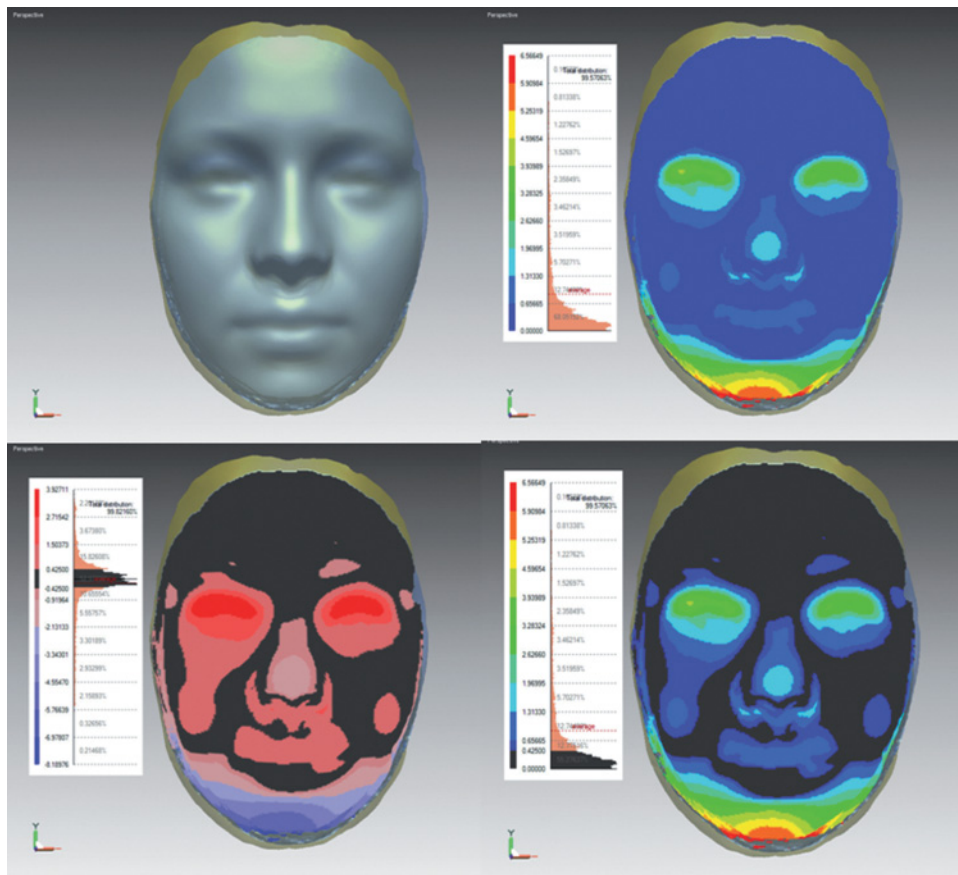


Figure 8.1 Three-dimensional extraction of data. Clockwise from top left: superimposition of two average shells (Slovenian and Egyptian); color map indicating the range of differences; color map with tolerance set at 0.425 mm showing a 59.01% similarity between shells; color map showing the mean difference between two shells as 0.48 ± 0.46 mm.

(Hou_Egy) for the male groupings. The linear differences ranged from 0.28 mm (Wel_Hou) to 0.87 mm (Slo_Egy). The results placed in ascending order of the mean values are presented in Tables 8.1 and 8.2.

Color histograms

Differences were also noted between the facial shells from the different subgroupings when color histograms were employed. The color histograms showed that the “similarities” in facial shells between gender subgroupings ranged from 26.70% (Hun_Egy) to 70.39% (Wel_Slo) for males, and 36.09% (Hou_Egy) to 79.83% (Wel_Hou) for females. The average linear distance from the signed color histograms for the male subgroupings ranged from -6.30 mm (Hou_Egy) to 4.44 mm (Hou_Slo). Those for the female subgroupings ranged from -6.32 mm (Slo_Egy) to 4.25 mm (Hou_Slo) (see Tables 8.1 and 8.2).

Table 8.1 The surface differences for the female populations: mean, standard deviation (SD), and minimum and maximum deviations

Females	Mean (mm)	SD (mm)	Minimum (mm)	Maximum (mm)
Wel_Hou	0.28	0.34	-3.40	1.28
Hun_Slo	0.46	0.44	-0.88	2.45
Wel_Hun	0.47	0.38	-2.16	1.45
Hou_Hun	0.55	0.59	-1.99	3.81
Wel_Slo	0.64	0.50	-2.02	2.56
Wel_Egy	0.70	0.79	-3.41	1.27
Hou_Slo	0.75	0.70	-2.02	4.25
Hou_Egy	0.75	0.68	-4.20	2.04
Hun_Egy	0.83	0.90	-4.21	3.64
Slo_Egy	0.87	1.27	-6.32	3.65

Egy; Egypt; Hou, United States of America (Houston, Texas); Hun, Hungary; Slo, Slovenia; Wel, United Kingdom (Wales).

Table 8.2 The surface differences for the male populations: mean, standard deviation (SD), and minimum and maximum deviations

Males	Mean (mm)	SD (mm)	Minimum (mm)	Max (mm)
Wel_Slo	0.37	0.41	-1.41	2.53
Hou_Hun	0.44	0.41	-1.98	2.07
Wel_Hun	0.45	0.38	-1.61	2.13
Wel_Hou	0.47	0.46	-1.18	2.42
Hun_Slo	0.47	0.40	-1.71	2.20
Hou_Slo	0.48	0.47	-2.00	4.44
Wel_Egy	0.69	0.81	-4.88	2.30
Slo_Egy	0.75	0.78	-4.15	2.41
Hun_Egy	0.91	0.79	-4.39	2.66
Hou_Egy	1.00	1.01	-6.30	2.41

Egy; Egypt; Hou, United States of America (Houston, Texas); Hun, Hungary; Slo, Slovenia; Wel, United Kingdom (Wales).

Surface areas/shapes

Surface area and shape differences between the different subgroupings are illustrated by the color histograms and surface mapping, and these are shown in Figures 8.2 and 8.3. Surface area comparisons between the Egyptian and all other templates varied the most for both the male and female faces. These discrepancies were most notably seen in the nose, maxilla, mandible, and chin areas. The least variability in the facial templates occurred in the Wel_Slo template for the males and Wel_Hou template for the females.

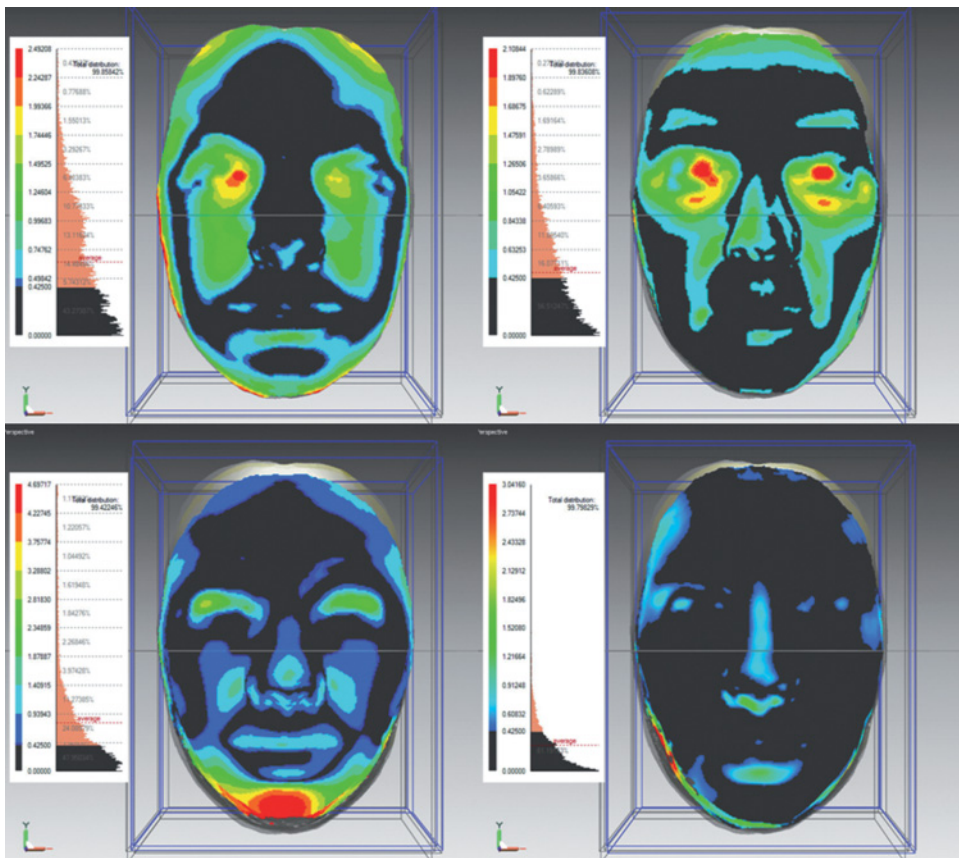


Figure 8.2 Three-dimensional morphologic analysis of population female variations. The color maps depict the areas of difference and the corresponding areas of similarity when the Welsh template is used.

WHAT THE FUTURE MIGHT HOLD?

This chapter describes the use of 3D facial averages in the study of five populations around the world. In addition, the 3D average faces were used as templates to compare the morphologic differences between the gender-specific populations.

The use of facial averages

3D average faces have been described previously in the literature and serve as an excellent basis for understanding complex 3D datasets.^{25,26} The use of facial templates has been demonstrated to be robust in representations of populations,^{27,28} and its uniqueness has been best illustrated by the distinct differences between male and female averages. Furthermore, Hutton and co-workers built dense surface models from 421 facial scans of subjects ranging from 1 to 80 years old.²⁹ It was noted in their study faces that a difference in methodology was represented. Faces were aligned based on 10 surface landmarks

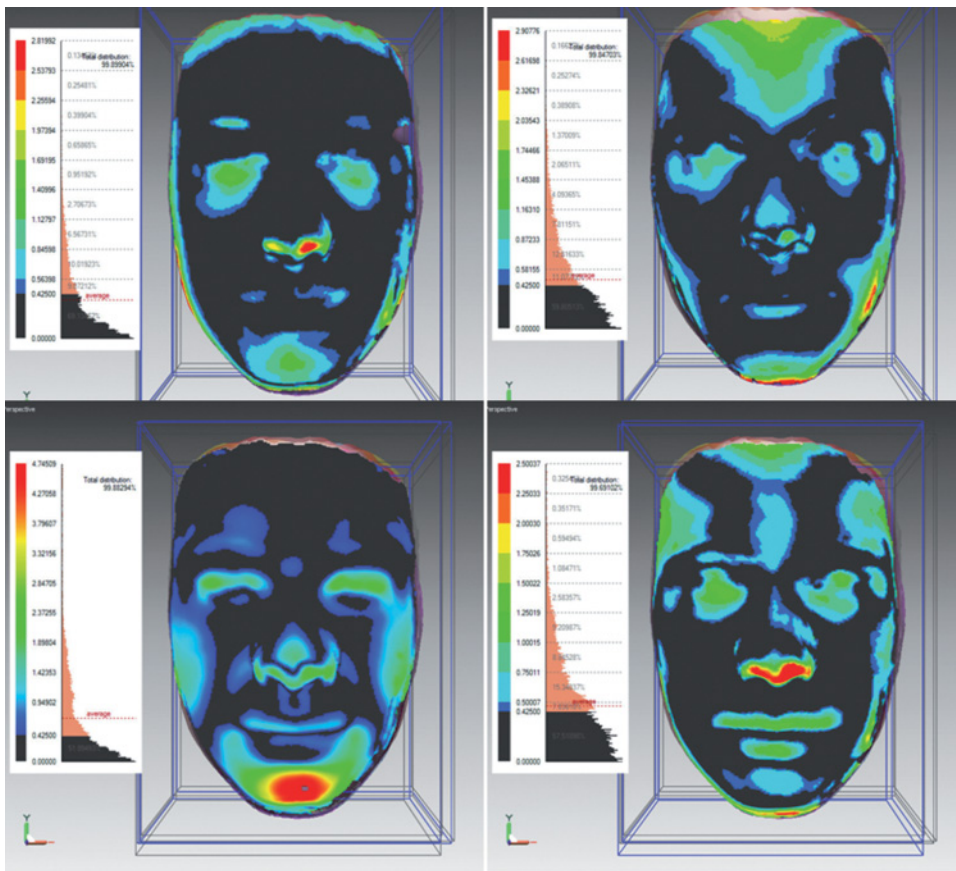


Figure 8.3 Three-dimensional morphologic analysis of population male variations. The color maps depict the areas of difference and the corresponding areas of similarity when the Welsh template is used.

before a combination of complex algorithms was applied to the faces. The final dense surface model used to help diagnose people with Noonan syndrome.³⁰

Average faces have also been described to compare treatment changes between extraction versus nonextraction groups,³¹ as well as cross-sectional growth changes among children.¹⁷ The average faces presented in this template capture the probable variation present within a representative population dataset.

Differences between all subgroups

Previous studies on the male facial average of two different ethnic groups (Japanese and European) have shown that there are distinctive differences between populations. These differences are in the orbital and cheek regions, and to a lesser extent in the jaw area. The authors postulated that the Japanese male face was flatter than the European male face.²⁸

From the results of comparing the linear measurements between subgroups, the current study was able to first determine that each individual average face was fundamentally different and unique. The range in the measurements, color histograms, and surface areas indicated that some facial averages were more similar to one another, whereas in others morphologic differences were much greater. This was most apparent when two totally different ethnic groups were studied (Egyptians and Europeans).

It was also noted that the differences in the mean values of surfaces were small but the amounts of variability (maximum and minimum variations) were high and concentrated to particular regions of the face. This was not unexpected as the individual subgroupings were different and had to be treated as separate entities. The color histograms best indicated these differences. For example, when European faces were compared with the Egyptian, the majority of the differences were found in the foreheads (the Egyptian faces having flatter sloping foreheads), stronger malars, and smaller chins, and the Egyptian ones tending to possess more bimaxillary protrusion.

The analysis of the European and North American populations showed greater similarities, reflected in the higher similarity percentages. Even though these similarity percentages were higher, the presences of differences were more concentrated to the areas of the face where orthodontic treatment might have an impact. For example, Slovenian females were more Class III in terms of skeletal pattern than were females from Wales or Houston (see Figure 8.2) and Hungarian males tended to be more Class II than males from Houston (see Figure 8.3).

Clinical implications in orthodontics

Most of the available data concerning facial soft tissues, particularly profiles, in orthodontics have been obtained from cephalometric data, with additional material from a small number of 3D studies. It has been shown in previous cephalometric studies that ethnic variations are present and need to be applied to orthodontics.^{32,33} In recent years, 3D surface acquisition imaging systems have been gaining popularity and have proven to be an accurate and reliable way to capture facial soft tissues.³⁴

In the present study, facial averages were used to compare the facial morphologic differences found between five populations. These five groups represented their respective population variation. Although populations of Caucasian descent showed the greatest similarities, they proved to exhibit distinct facial morphologic differences. It was obvious that each population had unique differences, particularly in different regions of the face. Furthermore, when a totally different ethnic population was included, a very large variation was observed.

Some studies have also commented on the prominence of the nose as a defining factor in population differences.³⁵ Others have commented that the soft tissue drape differs considerably between two similar groups of North American children, and that the relationship of soft tissues should seriously be taken into consideration.³⁶

The importance of these findings, especially in the realm of orthodontics, implies that baselines for facial morphologic norms for each population may be required in the near future. Studies such as these can be used to formulate normative databases that clinicians can use when predicting treatment for specific populations.² If the facial averages truly represent the norms for each population, the soft tissue profile as a final treatment outcome might need to be studied in greater detail. This study has also demonstrated that subgroupings in populations are different in accordance with their specific population groups. Therefore, as in traditional cephalometric studies, normative values may need to be readdressed and the new 3D norms created. An example here is when a female Class III skeletal pattern of Welsh descent is compared with the Slovenian, American (Houston), and Egyptian averages: the recorded values are all very different (Figure 8.4).

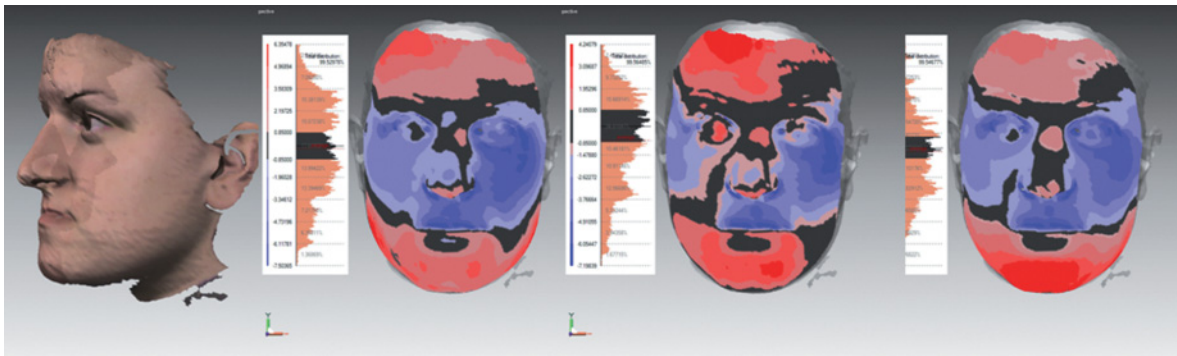


Figure 8.4 A comparison of a Class III Welsh female subject against a Houston, Slovenian, and Egyptian average. Although the pattern indicates a Class III pattern with mid-facial hypoplasia and a hyperplastic mandible, how these differences actually occur in size and magnitude vary.

CONCLUSION

Average faces can be efficiently and effectively created from a sample of 3D faces. These average faces can be used to compare differences in facial morphologies for different populations and genders, and it seems that an average face may be used to represent the ethnic norm of a population.

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A New Clinical Protocol to Plan Craniomaxillofacial Surgery Using Computer-aided Simulation

James J. Xia, Jaime Gateno, and John F. Teichgraeber

INTRODUCTION

Each year in the United States, a significant number of patients require craniomaxillofacial (CMF) surgery for the correction of congenital and acquired conditions of the head and face. The surgical correction of CMF deformities is complex and challenging. The success of these surgeries depends not only on the technical aspects of the operation, but also, to a larger extent, on the formulation of a precise surgical plan.^{1–10}

Over the last 50 years, there have been significant improvements in the technical aspects of surgery, that is, rigid fixation, resorbable materials, distraction osteogenesis, minimally invasive approaches, and so on. However, the planning methods have mostly remained unchanged,^{3,4,6,10} and the question still remains: Are the traditional methods really appropriate for planning CMF surgery? Traditional planning methods will be critically reviewed and a new protocol for planning CMF surgery using computer-aided surgical simulation (CASS) will be presented.

CRITICAL REVIEW OF TRADITIONAL METHODS USED TO PLAN CRANIOMAXILLOFACIAL SURGERY

In CMF surgery, surgical planning involves a series of logical steps. These steps include data-gathering, diagnosis and quantification of the condition, establishment of a preliminary surgical plan, surgical simulation, establishment of the final surgical plan, and transfer of the plan to the patient.

Initially, data are gathered from a multitude of difference sources. These include the physical examination, medical photographs, plain radiographs (e.g., cephalogram and orthopantomogram), computed

tomography (CT), and mounted plaster dental models.^{1,2} Each of these sources provides a portion of the whole dataset that is needed for successful planning. In practice, a surgeon evaluates each one of these studies in a sequential manner and creates a complete three-dimensional (3D) mental picture.

The next step in the planning process is the diagnosis and quantification of the deformity. In orthognathic surgery, an important part of this process is cephalometric analysis.^{1,11} After the surgeon has formulated the diagnosis, he or she develops a preliminary plan and, in many instances, alternative plans.

To test the feasibility of the preliminary plan(s), the surgeon then simulates the planned surgery. In orthognathic surgery, this is done by completing prediction tracings and dental model surgery.^{1,2} Prediction tracings are done by tracing the silhouette of the facial bones from a two-dimensional (2D) cephalogram onto a piece of acetate paper. These tracings are then cut and moved to evaluate possible outcomes. This task can also be completed in the computer.

Dental model surgery is then completed on plaster dental models that have been mounted on an articulator. This is undertaken by physically cutting the models and moving them to the desired position. In other types of surgery (e.g., trauma, pathology, and reconstruction), the extent of surgical simulation is even more limited. In clinical practice, most of these surgeries are not simulated. Sometimes, doctors obtain CT-based rapid prototyping physical models (e.g., stereolithography) to simulate skeletal surgery. After the simulation has been completed, a surgeon formulates the final surgical plan.

The last step in the planning process is to transfer the surgical plan to the patient at the time of surgery. In orthognathic surgery, the surgical plan is transferred to the patient prior to surgery by using surgical splints and selected measurements. The splints are fabricated on the same plaster dental models on which the surgery was simulated. In CMF surgeries that do not involve dentition, surgeons currently do not have a method of transferring the surgical plan to the patient. Although certain measurements taken during the planning process can be used to guide surgery, most of the time the process is more of an art than a science. There have been reports on the use of surgical navigation for this purpose,¹²⁻¹⁵ but this technique has not been universally adopted.

There are a number of problems associated with the traditional planning system. First, the coordinate systems of various datasources used for surgical planning are different. The physical examination and the medical photographs are taken with the patient's head oriented to the natural head position (NHP). The cephalogram is oriented to the Frankfort horizontal plane, and the articulated dental models are oriented to the axis-orbital plane.¹⁶ On average, these planes differ from each other by about 8 degrees.¹⁶ Currently, most surgeons are unaware of this problem and fail to account for the differences. This discrepancy alone can be responsible for a 15% difference in maxillary projection between the planned and the actual outcomes.¹⁶

In addition, using the traditional method, surgeons are not able to visualize the whole dataset in three dimensions.^{3-5,10,17,18} Instead, the surgeons have to create this picture in their minds. This creates a problem communicating with the other members of the treatment team. Clearly, it is impossible to assure that all involved have the same picture.

The analysis is 2D and only measures structures in a single plane. It may be appropriate for patients with symmetric deformities, but is inadequate for patients with asymmetric conditions.^{3,8} It has been reported that 34% of patients with dentofacial deformities have asymmetric conditions.¹⁹

Next, there may be inaccurate orientation of the dental models mounted on an articulator. The occlusal plane inclination of the dental models mounted on a semi-adjustable articulator is on an average 8 degrees steeper than the actual inclination of the occlusal plane.^{16,20} In addition, there are design flaws in the current devices used to orient the dental models on an articulator (i.e., the facebow). A patient can easily tilt the facebow during the registration process, creating an inaccurate recording of the

occlusal cant (the roll of the maxilla). An inaccurate initial model position will always create an inaccurate plan.²⁰

Dental model surgery is undertaken for two purposes. The first is to establish the occlusion, and the second is to reorient the models to ensure that the bones are placed in the ideal position at surgery. Because plaster dental models do not depict the surrounding bones, the surgeon is unable to visualize the effects of model position on the facial skeleton.^{5,6,21} Therefore, the ability to obtain the ideal bone position becomes a random event.^{4,6,7}

Prediction tracings and the plaster model surgery are two separate processes, which are often inaccurate and time-consuming.^{3,22,23} Currently, an experienced surgeon spends 3–5 hours completing these steps, which is another drawback.²⁴

In addition, the CT-based rapid prototyping models are costly (a single model costing, at the time of writing, about \$2500), and they are unable to simulate different iterations of a given plan on a single model.¹⁷ Once the model has been cut, the cut cannot be undone. They also fail to render the teeth with the precision necessary for surgical planning.^{3,4,10}

Finally, the fabrication of splints is time-consuming. A busy surgeon performs several of these operations per week, and many patients require two splints (intermediate and final). The fabrication of each splint may take an additional hour.^{2,24} Moreover, for surgery that does not involve the dentition, surgeons do not have a way of transferring the surgical plan to the patient.^{3,6,8,13}

CLINICAL SURGICAL PLANNING PROTOCOL

It is clear that many of the unwanted surgical outcomes are the result of deficient planning. The need to improve the traditional surgical planning methods has led our group to develop a 3D CASS system to plan CMF surgery. We have utilized this system in maxillofacial surgery,^{9,25–27} craniofacial surgery,²⁸ trauma, and distraction osteogenesis.^{28–30} Using this system, doctors can perform “virtual surgery” and create a 3D prediction of the patient’s surgical outcomes as if they were performing surgery in the operating room. We have documented the clinical feasibility,^{4,10} the accuracy,³¹ and the cost-effectiveness²⁴ of this system. Our CASS system incorporates three distinctive features and innovations:

- Multiple imaging modalities are used to create an accurate model of the craniofacial skeleton.
- Special techniques are employed to orient the computerized bone model in the NHP.
- Computer-aided design (CAD)/computer-aided manufacturing techniques are used to fabricate accurate surgical splints and templates to transfer the surgical plan to the operating room. Our CASS planning protocol is presented as follows.

Step 1: Clinical examination and anthropometric measurements

A complete clinical examination and anthropometric measurements are essential for the clinical decision-making process.^{1,32,33} They should be performed based on the patient’s NHP. This information provides not only static, but also extremely valuable dynamic information (see Chapter 2 for details).

Step 2: Creation of a computerized composite skull model

A composite skull model is a computerized CT model that simultaneously displays an accurate rendition of both the bony structures and the teeth. Although 3D CT scans have been successfully used to visualize

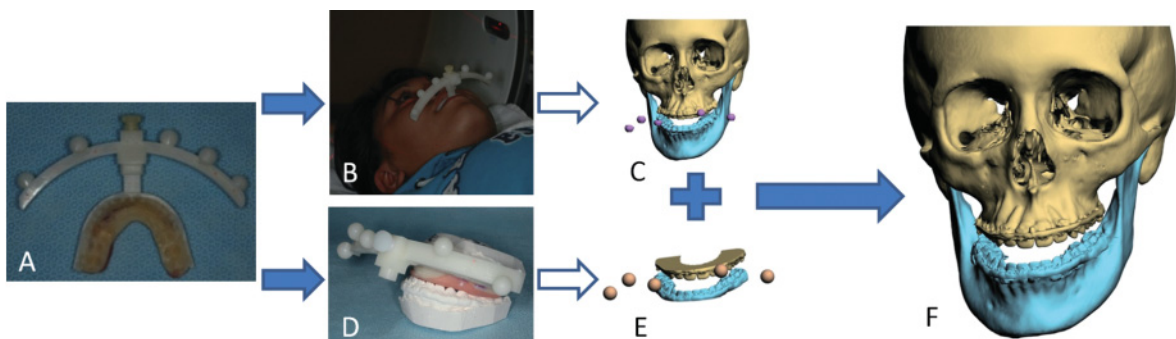


Figure 9.1 (A) Facebow with fiducial markers is attached to the bite-jig. (B) The patient bites on the bite-jig and a computed tomography scan. (C) Three separate but correlated computer models are reconstructed: a midface model, a mandibular model, and a fiducial marker model. (D) The bite-jig and facebow are placed between the upper and lower plaster dental models during the scanning process. (E) Three separate but correlated computer models are also reconstructed: an upper digital dental model, a lower digital dental model, and a fiducial marker model. (F) By aligning the fiducial markers, the digital dental models are incorporated into the 3D computed tomography skull model. The computerized composite skull model is thus created. It simultaneously displays an accurate rendition of both the bony structures and the teeth.

the patient's condition, they have not been successfully used for surgical simulation because the CT does not render the teeth with the accuracy that is necessary for surgical simulation.

In order to replace the inaccurate dentition in the 3D CT model, a composite skull model is used in the surgical planning process by incorporating accurate digital dental models into a 3D CT model of the face.^{21,34} This is achieved by merging two separate digital datasets: the digital dental models and the 3D CT. The merger of the separate datasets is undertaken by utilizing fiducial markers (common reference points) between the two sets. The fiducial markers utilized in this protocol are spheres that are part of a plastic facebow. The facebow is attached to an acrylic bite registration that is placed in the patient's maxillary and mandibular dental arches and plaster models before they are scanned (Figure 9.1A).

To fabricate the solid bite jig, a bite registration is taken using low-shrinkage material (e.g., LuxaBite; Chemisch-Pharmazeutische Fabrik GmbH, Hamburg, Germany). The bite registration material is first placed on a bite-jig, and the impression is taken on the occlusal surfaces of the upper teeth. After the material has hardened, additional material is added on the mandibular side of the jig. The mandibular bite registration is captured in a centric relationship.

Once the bite registration has been created, it is attached to the facebow. A CT scan of the patient's craniofacial skeleton is obtained while the patient is biting on the bite registration (Figure 9.1B). The CT scan is completed using the standard scanning algorithm, a matrix of 512×512 at 0.625 mm slice thickness, 25 cm or less field of view, 0 degrees gantry tilt, and 1:1 pitch. Once the CT scan has been obtained, it is segmented and three separate but correlated computer models are generated: a midface model, a mandibular model, and a fiducial marker model (Figure 9.1C). The digital dental models are then created by scanning the plaster dental models, the bite-jig, and the facebow (Figure 9.1D).

The bite-jig and facebow are placed between the upper and lower plaster dental models during the scanning process (Figure 9.1D). This can be done with a surface scanner (resolution 0.1 mm or higher) or with a micro-CT scanner (resolution 7–75 μm). This generates three separate but correlated computer

models: an upper digital dental model, a lower digital dental model, and a fiducial marker model (Figure 9.1E).

After the 3D CT models and the digital dental models have been obtained, the teeth on the CT skull model are removed, leaving the fiducial markers in place. The upper and lower digital dental models with their corresponding fiducial markers are imported into the CT skull model. By aligning the fiducial markers, the digital dental models are incorporated into the 3D CT skull model. The fiducial markers are then marked hidden. This results in a computerized composite skull model that simultaneously displays an accurate rendition of the bones and the teeth (Figure 9.1F).^{4,10,21,34,35}

Step 3: Reorientation of the composite skull model to the natural head position

A digital gyroscope is attached to the same facebow. With the patient in the NHP, the pitch, roll, and yaw of the face are recorded and used to reorient the composite skull model.^{36–39} In the computer, a digital replica (CAD model) of the gyroscope is registered to the composite skull model (via the fiducial markers), and the two objects are attached to each other. Afterwards, the recorded pitch, roll, and yaw are applied to the center of the gyroscope replica, reorienting the composite skull model to the NHP (Figure 9.2).

Step 4: Analysis and quantification of the deformity

In CASS, the analysis and quantification of the deformity is completed in both two and three dimensions. In order to facilitate this task, a unique 3D reference system is initially constructed for the composite skull model. The reference system has its origin at the soft tissue nasion and consists of three orthogonal

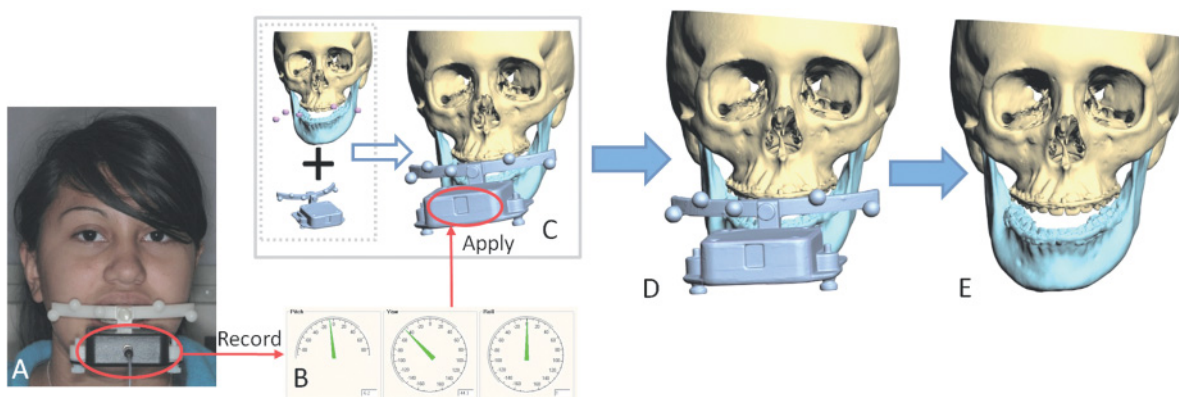


Figure 9.2 Orientation of the composite skull model to the natural head position (NHP) using the digital gyroscope method. (A) A digital gyroscope is attached to the bite-jig and facebow. (B) The pitch, roll, and yaw of the gyroscope are recorded. (C) In the computer, a digital replica (computer-aided design model) of the gyroscope is registered to the composite skull model (via the fiducial markers), and the two objects are attached to each other. (D) The recorded pitch, roll, and yaw are applied to the center of the gyroscope replica, reorienting the composite skull model to the NHP. (E) After the composite skull has been orientated to the NHP, the gyroscope replica is marked as hidden.



Figure 9.3 A cephalogram is emulated using volume-rendering to project the computed tomography voxels onto the sagittal plane.

planes: sagittal, coronal, and axial. The sagittal plane in the reference system is the patient's true mid-sagittal plane.

Once the composite model has been positioned in the 3D reference system, the user digitizes the selected cephalometric landmarks and chooses the desired analysis. Some landmarks are hypothetically located on the midsagittal plane, that is, the sella. In order to digitize these landmarks, the software will emulate a 2D cephalogram by a volume-rendering algorithm (i.e., ray-casting algorithm). This projects the CT voxels onto a sagittal plane (Figure 9.3). Once the landmark digitization has been completed, the computer automatically performs all the necessary calculations and presents the cephalometric results.

In the 3D analysis, we examine anatomic structures for symmetry. To examine the symmetry of the maxilla, we have developed a method based on the work of Grayson.^{40–42} In this method, a triangular spline is created on the maxillary dentition by digitizing three landmarks: the maxillary dental midline and two corresponding landmarks on the right and left molars (usually the mesiobuccal cusp of the maxillary right and left first molars; Figure 9.4). The software reads the x -, y -, and z -coordinates of each vertex of the triangle to automatically calculate the pitch, roll, and yaw of the maxilla as well as the maxillary midline deviation. The pitch represents the maxillary occlusal plane, while the roll and yaw represent the occlusal cant and the horizontal discrepancy.

In some instances, because of the difficulty interpreting some 3D data and the unavailability of the 3D normative data (see Chapter 1 for details), we still use a conventional 2D analysis, in which all the 3D landmarks are projected onto the mid-sagittal plane ($x = 0$). The same landmarks located on the right and the left sides are averaged in the y - and z -axes. In this mode, we make decisions regarding anteroposterior projection, vertical position, and inclinations of the occlusal plane and mandibular plane (pitch).

In addition to the 2D and 3D measurements, the software is also able to perform volumetric measurements. These measurements have proven to be useful in the quantification of airway and orbital volumes (Figure 9.5).

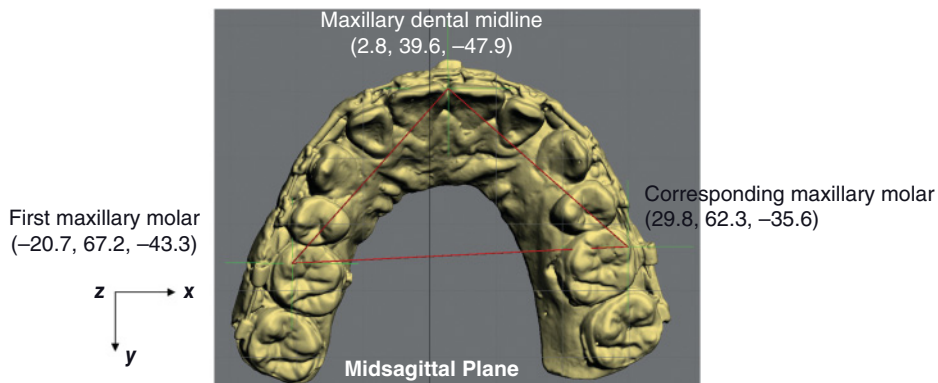


Figure 9.4 In triangle method, a triangular spline is created on the maxillary dentition by digitizing three landmarks: the dental midline, the mesiobuccal cusp of the maxillary right first molar, and the mesiobuccal cusp of the maxillary left first or corresponding molar. The software reads the x -, y -, and z -coordinates of each vertex of the triangle to automatically calculate the pitch, roll, and yaw of the maxilla, as well as the maxillary midline deviation. The pitch represents the maxillary occlusal plane, while the roll and yaw represent the occlusal cant and the horizontal discrepancy.

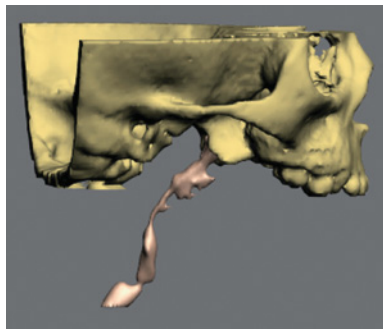


Figure 9.5 Volumetric measurements are used to measure the size of the airway and orbital volumes.

Step 5: Simulation of surgery in the computer

Any type of osteotomy can be simulated in this CASS system – Le Fort I, sagittal split, genioplasty, etc. After the bones have been osteotomized, the user can move and rotate the bony segments to the desired position.

In patients requiring bimaxillary surgery, the maxillary surgery is usually simulated first. The maxilla is first repositioned symmetrically. The triangular spline used to quantify the maxillary asymmetry is “glued” to the maxilla so that any movement of the triangle is automatically transferred to the maxilla. The software reads the x -, y -, and z -coordinates of the triangle vertices and calculates the discrepancy between the right and left. It then automatically moves the upper dental midline to the mid-sagittal plane,

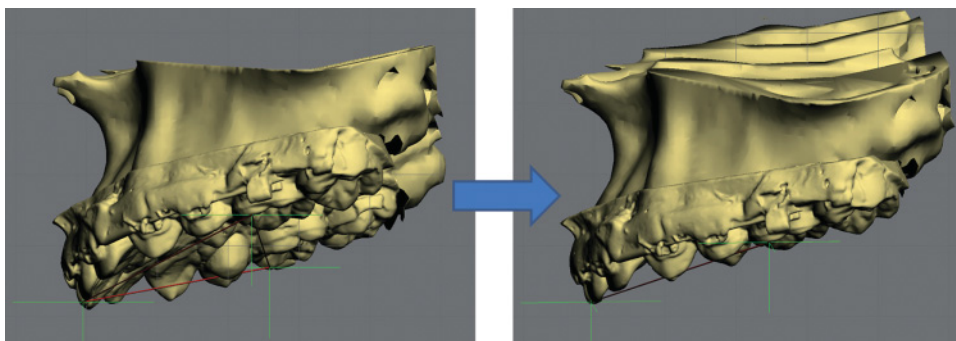


Figure 9.6 The triangular spline used to quantify the maxillary asymmetry is “glued” to the maxilla. The computer reads the x-, y-, and z-coordinates of the triangle vertices and moves them to symmetry (0 degrees of roll, 0 degrees of yaw). The movement of the triangle is then automatically transferred to the maxilla.

and rotates the triangle to symmetry (0 degrees of roll, 0 degrees of yaw; Figure 9.6). This triangular method works especially well when the dental arch itself is symmetric. If the dental arch is asymmetric, the doctor’s intervention may be required to move/rotate the maxilla to the most balanced position. After the asymmetry of the maxilla has been corrected, the maxillary pitch (occlusal plane inclination) is adjusted and the maxilla is moved anteroposteriorly and superoinferiorly to the desired position based on the cephalometric analysis and clinical measurements.

After the maxilla has been placed in its final position, the distal segment of the mandible is moved to maximal intercuspation (MI). Unfortunately, the establishment of MI on the computer is difficult. It is almost impossible to be certain that what is seen on the computer truly represents the best possible alignment. To ensure that the digital final occlusion is at its correct MI, the plaster models are first physically positioned in MI (final occlusion) and then scanned in this position. The scanned models are incorporated into the composite skull model to guide the precise placement of the distal mandible into MI. Once the distal segment is in position, the proximal segments of the mandible are aligned. If necessary, a genio-plasty is also simulated.

In some instances, the repositioning of the osteotomized segments is not sufficient to recreate facial symmetry. This is due to the fact that in many patients with facial asymmetries, the bones are not only asymmetrically displaced but also differ in size and shape from one side to the other. Therefore, it is still necessary to evaluate the symmetry after the simulation of the jaw movements. To help with this, the mirror-imaging tool is used. One half of the face (the healthy side) is selected, copied, mirror-imaged (flipped), and superimposed on the contralateral side (Figure 9.7). The differences between the two sides are then calculated using a Boolean operation. Based on this information, the surgeon may decide to add volume (grafting), remove volume (ostectomy), or adjust the position of the segments (camouflage).

Step 6: Transfer the computerized plan to the patient

After the surgical plan has been finalized, it is necessary to transfer the plan to the patient at the time of the surgery. Surgical dental splints or surgical templates can be created for this purpose. Surgical dental splints are used to reposition dentate bony segments, while surgical templates are used to reposition

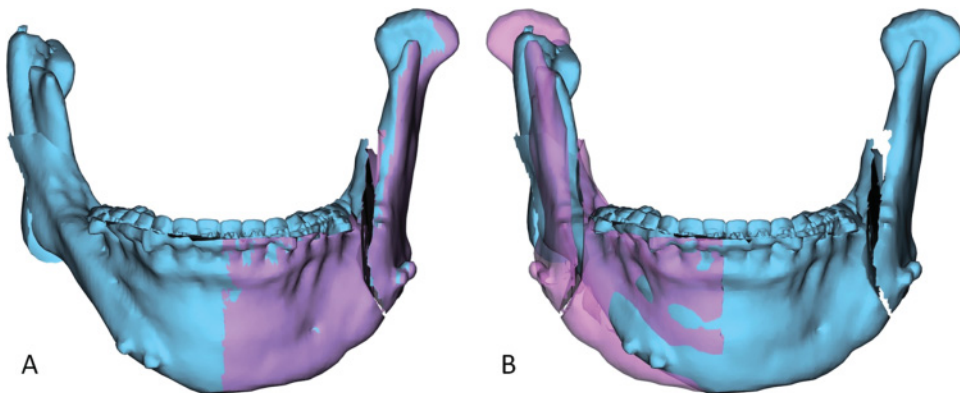


Figure 9.7 In the mirror-image routine, one half of the face is (A) selected, and (B) copied, mirror-imaged (flipped), and superimposed onto the contralateral side.

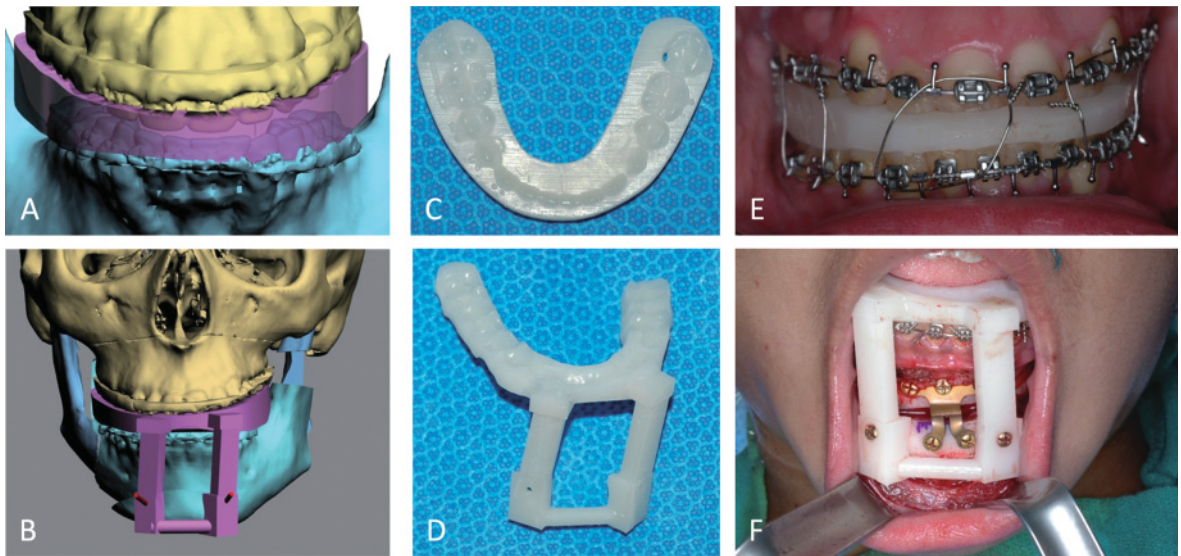


Figure 9.8 Surgical dental splints and templates are created using the authors' computer-aided design/computer-aided manufacturing technique. (A) Digital surgical splint. (B) Digital chin template. (C) Physical surgical splint. (D) Physical chin template. (E) The use of a physical surgical splint at the time of the surgery. (F) The use of a physical chin template at the time of surgery.

nondentate ones. The surgical dental splints are created by inserting a digital wafer between the maxillary and mandibular dental arches. A Boolean operation is then performed, resulting in a digital surgical splint (Figure 9.8A). The surgical templates record the 3D surface geometry of the area of interest so that they fit onto the bone in a unique position (Figure 9.8B). The system can export the digital splints and templates in .stl format. These are fabricated using a rapid prototyping machine (Figure 9.8C, D), and subsequently used at the time of the surgery (Figure 9.8E, F).

CONCLUSION

With the computer-aided surgical simulation protocol, we are now able to treat patients with significant asymmetries in a single operation, whereas this was in the past completed in two stages. We are also able to simulate different surgical procedures in order to create the appropriate plan. The computerized surgical plan is then transferred to the patient in the operating room using computer-generated surgical splints and templates.

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10

Controversial Issues in Computer-aided Surgical Planning for Craniomaxillofacial Surgery

James J. Xia, Jaime Gateno, and John F. Teichgraber

INTRODUCTION

With the new computer simulation technology, we are able to create three-dimensional (3D) models of the face that incorporate accurate renditions of the teeth, the skeleton, and the soft tissues. Moreover, these models can be oriented to a certain reference head orientation, that is, the natural head position (NHP). From this, one may infer that the value of the physical examination in the clinical decision-making process will become irrelevant, but in our experience, this is far from true. Although these models can capture the anatomy in great detail, they are static and only present the status of the tissues at the time when the image was captured. The physical examination still provides us with extremely valuable dynamic information that cannot be obtained from any other source. To illustrate this, we will discuss several pitfalls that can be encountered by relying only on static images.

MANDIBULAR LATEROGNATHIA

The first example is a patient with significant mandibular laterognathia (lateral chin deviation; Figure 10.1A). On assessing the alignment of the maxillary dental midline, we have discovered that, in some of these patients, the relationship of the maxillary dental midline to the upper lip varies depending on the mediolateral position of the chin.

During the physical examination, we first measure the transverse alignment of the maxillary dental midline to the middle of the upper lip while the patient is in a centric relationship. In this position, the maxillary dental midline seems to be deviated opposite to chin deviation (Figure 10.1B). We then measure the same alignment after we have asked the patient to move his chin to the midline, simulating correction

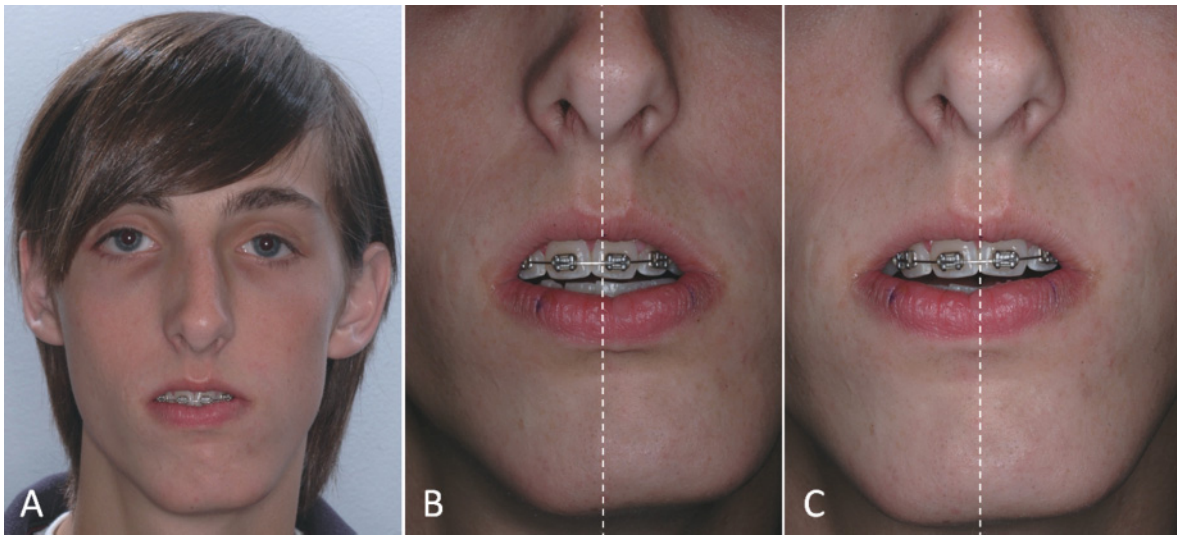


Figure 10.1 The deviation of maxillary dental midline changes depending on different mandibular positions. (A) A patient with significant mandibular laterognathia (lateral chin deviation). (B) The maxillary dental midline seems to be deviated opposite to the chin deviation while the patient is in a centric relationship. (C) The maxillary dental midline is no longer deviated after we have asked the patient to move his chin to the midline simulating correction of the mandibular asymmetry.

of the mandibular asymmetry. In this position, the maxillary dental midline is no longer deviated (Figure 10.1C).

What is happening here is that the lateral displacement of the mandible is producing a deformation of the upper lip by dragging it to the side of the chin deviation. When the chin is moved to the midline, the upper lip regains its normal shape. The pitfall here is that if this dynamic deformation is not taken into account, the surgeon will “correct” a maxillary dental midline deviation that is nonexistent. Obviously, this will create an unwanted outcome. Therefore, we recommend that the decision to correct a maxillary midline deviation should be based on physical examination rather than on study images.

POSTURE

Another example of a possible pitfall of simply relying on static images is assessment of the amount of maxillary incisal show. The amount of incisal show varies with the patient’s position. It tends to decrease when the patient changes position from supine to sitting, and to standing (Figure 10.2).

The measurement of the incisal show on an acquired static image is important, in particular the uncertainty of the functional state of the lips. Ideally, the upper and lower lips should be in repose during the measurement. However, the functional state of the lips is questionable unless the surgeon is present during the scanning. Strained lips will produce an inaccurate determination of the incisal show. In addition, the computed tomography (CT) and cone beam CT (CBCT) images are usually acquired when the



Figure 10.2 The amount of maxillary incisal show may vary with the patient's position. (A) Incisor show in the standing position. (B) Incisor show of the same subject in a supine position.

patient is biting in occlusion. Therefore, it is best to determine this parameter clinically during the physical examination rather than relying on the computer images.

During the physical examination, this parameter should be measured with the patient standing in front of the surgeon. The decision of how much to change the amount of incisal show should not be based solely on the amount of show at rest. Other important issues should also be taken into account as well. These include the amount of gingival show during smiling, the presence of delayed passive eruption, and the presence of attrition. Finally, clinical measurements of the occlusal cant, degree of dystopia, and ear position also serve to verify that the composite skull model is correctly oriented in the 3D coordinate system.

NATURAL HEAD POSITION

An important prerequisite for accurate planning is to orientate the 3D composite skull model to a reference position. In two-dimensional (2D) cephalometry, the reference planes are usually the Frankfort horizontal plane and sella–nasion plane. However, many patients with craniomaxillofacial deformities have significant asymmetries of the upper face and skull base, and common intracranial cephalometric landmarks and planes often cannot be used to orient the composite skull model. The use of the NHP obviates the need for intracranial landmarks and provides a reproducible reference framework.

Currently, there is still debate over how to record the NHP and transfer it to the 3D model. The simplest method is to “eyeball” the 3D model in the computer and orient it to a balanced position based on the physician’s best estimate. Although it is not the patient’s true NHP, it may work if the craniofacial structures are symmetric. However, when the upper face and skull base have significant asymmetry, this

method is more an art than a science. It is the authors' opinion that NHP should be recorded directly when the patient is in NHP.

Can the NHP be recorded during CT scanning? If a medical CT scanner is used, the patient is in a supine position. In this case, it is impossible to position the patient's head in NHP during the scanning. If a CBCT scanner is used, the patient is in a sitting or standing position. A chin rest is required to stabilize the patient's head to ensure the quality of the CT images, because the shortest acquisition time is 5 seconds.¹ Although it is possible to position the patient's head in NHP without the chin rest, the quality of CT images is compromised. Clearly, it is necessary to develop a technique to record the patient's NHP and accurately transfer it to the 3D model.

Our laboratory has developed two techniques to reorient the composite CT model to the NHP. The first utilizes a digital gyroscope, and the second utilizes a calibrated 3D laser surface scanner. In both methods, the NHP is established using the modified Mølhave method.² The patient faces a blank wall at a distance of 2m in an isolated standing or sitting position. The patient is then asked to establish the NHP by flexing and extending the head and then balancing in a position of comfort while looking straight ahead without a specific focus. The digital gyroscope technique is the one we are currently using in our clinical practice (see Figure 10.2).

The second technique is the laser surface scanner method. With this technique, the surface geometry of the facial soft tissues is captured while the patient is in NHP. During the scanning, the patient is sitting on a calibrated chair at the center of the scanner. The scanner creates a correctly oriented 3D image of the face. The soft tissues of the composite model are then rendered, and the model is aligned to NHP by matching its soft tissues to the scanned image (Figure 10.3).^{3,4}

The advantages of the gyroscope technique are cost and convenience. The gyroscope costs a hundred times less than the laser scanner, is portable, and requires little maintenance. In addition to the methods described above, other techniques may be used to record the NHP. These include the use of a 3D digitizer

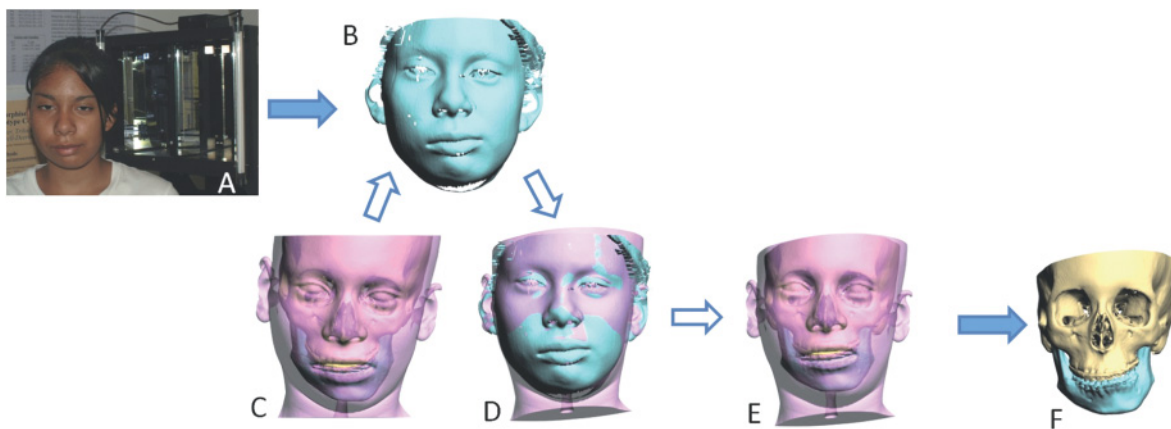


Figure 10.3 Orientation of the composite skull model to the natural head position (NHP) using the laser scanner method. (A) The surface geometry of the facial soft tissue is captured while the patient is sitting on a calibrated chair at the center of the laser scanner. (B) The captured surface geometry (scanned image) of the facial soft tissue. (C) A soft tissues model is rendered by computer, and the composite model is "glued" to the soft tissue model. (D) The soft tissue model is aligned to the NHP by matching it to the scanned image. (E) Both the soft tissue and composite skull models are thus oriented to the NHP. (F) The composite skull model is in the NHP after the soft tissue has been hidden.



Figure 10.4 The photographic method utilizes a calibrated camera to take orthogonal lateral and frontal photos when the patient is in the natural head position. The recorded natural head position is then transferred to a three-dimensional composite model on the computer.

and photographs (Figure 10.4).⁵ In the latter method, lateral and frontal photos are taken orthogonally using a camera that is calibrated to the true vertical plane.

QUANTIFYING CRANIOMAXILLOFACIAL DEFORMITIES

Craniofacial assessment is traditionally analyzed in two dimensions. Therefore, the most current anthropometric tables and cephalometric norms are still 2D. In the case of traditional cephalometry, all structures are projected onto a single plane, and bilateral landmarks are averaged. With the availability of advanced computer technology, we are now able to perform these analyses in 3D. The cephalometric landmarks exist three-dimensionally, and thus true 3D measurements can be made. This is especially useful in examining anatomic structures for symmetry, that is, maxillary asymmetry. However, some 3D measurements are often difficult to interpret. This is especially true for those 3D measurements which are directly translated (expanded) from their original 2D form.

For angles that theoretically exist in the sagittal plane (e.g., the sella–nasion point B [SNB]), the difference between the 3D measurements and the 2D measurements is relatively minor and clinically insignificant. An example of this is a patient with significant laterognathia (lateral chin deviation). In this patient, point B is displaced laterally and the 3D SNB angle on this patient differs only slightly from its 2D counterpart (Figure 10.5).

For angles that do not lie on the sagittal plane (e.g., gonial angle [Ar–Go–Me]⁶), the difference between the 3D measurements and the 2D measurements can be significant. In a 2D analysis, the change in this

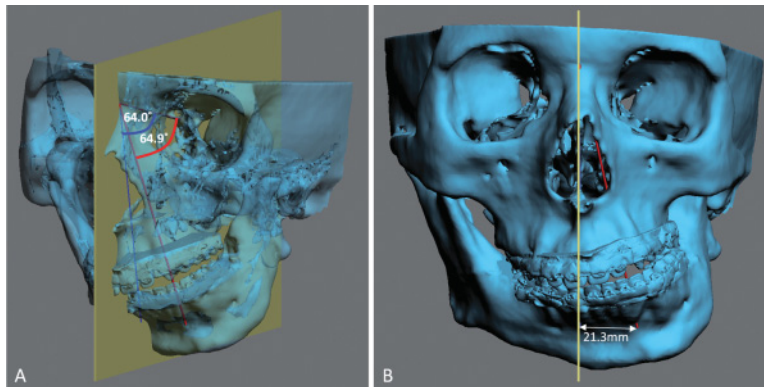


Figure 10.5 For angles that theoretically exist in the sagittal plane (e.g., the sella–nasion point B [SNB]), differences between three-dimensional measurements and two-dimensional measurements are relatively minor and clinically insignificant. (A) The SNB was measured as 64.9 degrees three-dimensionally (in red), while the projection of SNB on the midsagittal plane is measured as 64.0 degrees (in blue). (B) Point B is deviated 21.3mm to the left.

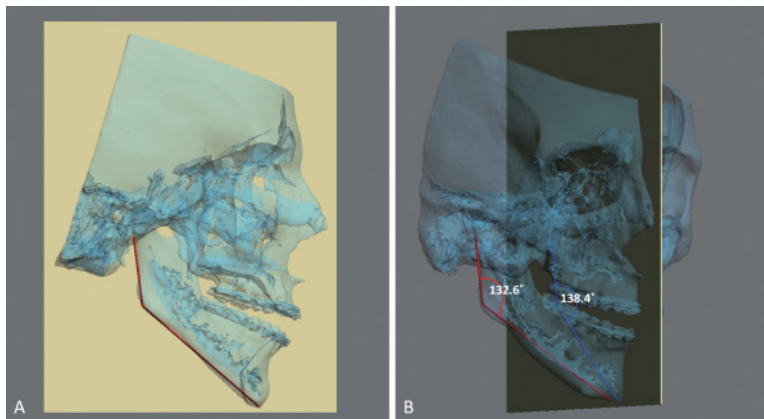


Figure 10.6 The mandibular condyles (Ar) and the gonial angles (Go) are on the lateral side of the face and are significantly separated from the midsagittal plane where the menton (Me) is located. (A) The lateral view of both two-dimensional and three-dimensional gonial angles (Ar–Go–Me). They look like the same. (B) The gonial angle (Ar–Go–Me) is measured as 132.6 degrees three-dimensionally (in red), whereas the projection of the gonial angle on the midsagittal plane is measured as 138.4 degrees (in blue).

angle is easy to interpret. If this angle is outside the normal range, it can be said that the “bend” of mandible is abnormal. The same is not necessarily true, however, in a 3D analysis. Anatomically, the mandibular condyles (Ar) and the gonial angles (Go) are on the lateral side of the face and are significantly separated from the sagittal plane, where the menton (Me) is located. Three-dimensionally, the gonial angle is described by a line that goes from Ar (top) to Go (bottom), and another one that goes from Go anteromedially to Me. The size of this 3D angle differs from the size of its 2D projection on the sagittal plane (Figure 10.6).

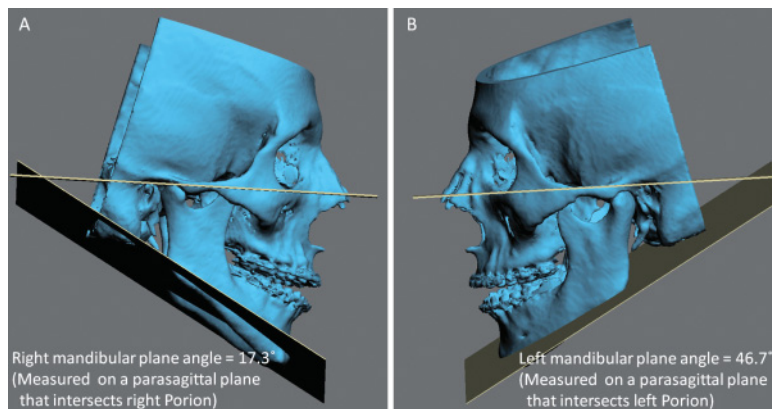


Figure 10.7 The mandibular plane angle is made by the intersection of the mandibular plane and the Frankfort horizontal plane. In this illustration, the mandibular plane is simply created by three points: right gonion, left gonion, and menton. The Frankfort horizontal plane is more complicated. It is created by the least-square averaged four points of the right and left porion and right and left orbitale. Since the right and left landmarks are not symmetric, the two planes diverge from each other in all planes of space. The size of the angle between the planes varies depending on where it is measured. (A) Right view. The right three-dimensional mandibular plane angle is 17.3 degrees measured on a parasagittal plane that intersects the right porion. (B) Left view. The left three-dimensional mandibular plane angle is 46.7 degrees measured on a parasagittal plane that intersects the left porion.

ANGULAR MEASUREMENTS

Another major problem in 3D cephalometry is the uncertainty of how angles are constructed by planes, for example the mandibular plane angle and occlusal plane inclination. For example, the mandibular plane angle is made by the intersection of the mandibular plane and the Frankfort horizontal plane. Geometrically, a plane can only be constructed by three points. For the mandibular plane, these points are right gonion, left gonion, and menton.⁷ For the Frankfort horizontal, the situation is more complicated. Theoretically, this plane is made up of four points: the right and left orbitale and the right and left porion. Unfortunately, most of the time, these points are not in the same plane. This situation begs the question: How should the plane be defined? Should one of the points be ignored? Should we average two points, three points, or all four?

This problem becomes more complicated when the patient has an asymmetric deformity. In this scenario, the right and left landmarks are not symmetric. Therefore, the two planes diverge from each other in all planes of space. In this situation, the size of the 3D angle between the planes varies depending on where it is measured (Figure 10.7).

ASSESSMENT OF THE OCCLUSAL PLANE

Finally, there is the whole question of the angular measurement of the occlusal plane inclination to the true horizontal plane. The occlusal plane is constructed by three points: (1) the mean of the two upper central incisor landmarks and the two lower central incisor landmarks, (2) the mean of the right upper

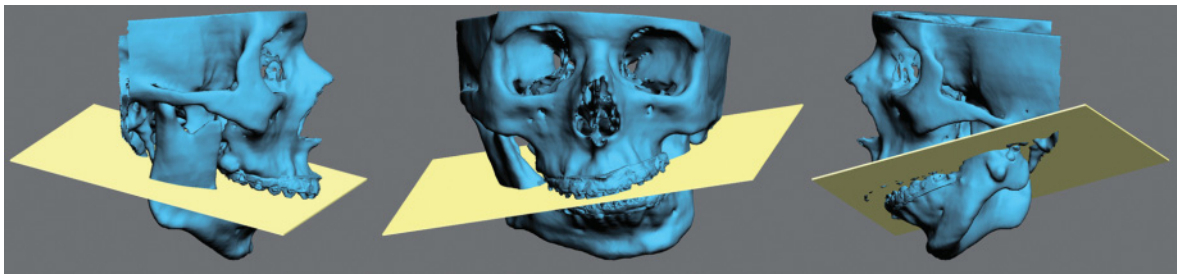


Figure 10.8 A patient has a significant occlusal cant and yaw discrepancy. In this illustration, the occlusal plane inclination angle is constructed by three points: (1) the mean of the two upper central incisor landmarks and the two lower central incisor landmarks, (2) the mean of the right upper and lower molar cusp landmarks, and (3) the mean of the left upper and lower molar cusp landmarks. The three-dimensional (3D) angle between the occlusal inclination and the true horizontal planes is 15 degrees if it is measured perpendicular to the intersection of the two planes. If it is measured on a parasagittal plane that intersects the right porion, the right 3D angle is 9.5 degrees. If it is measured on a parasagittal plane that intersects the left porion, the left 3D angle becomes 28.5 degrees.

and lower molar cusp landmarks, and (3) the mean of the left upper and lower molar cusp landmarks.⁷

In 2D cephalometry, the right and left landmarks are averaged and projected onto the sagittal plane. In 3D cephalometry, when the patient has a significant occlusal cant and yaw discrepancy, this 3D angle is measured as a combination of pitch, roll, and yaw of the maxillary dental arch (Figure 10.8). How do we interpret this measurement that represents the 3D information of the occlusal plane in a single value? Should we measure it from right and left and then average it? Should we first correct the maxillary asymmetry to solve the cant (roll) and yaw problems using the method introduced in Chapter 9, and then measure the occlusal plane inclination (pitch)? Or would it be better if we completely disregarded this measurement and created a new set of true 3D measurements to represent the pitch, roll, and yaw of the maxillary dental arch?

CONCLUSION

In conclusion, computer-aided surgical planning is a new and evolving tool in the treatment of patients with craniomaxillofacial deformities, but it does not preclude the need for an accurate clinical examination. A number of controversies still exist with regard to its application, most notably the application of the NHP and the utilization of 3D cephalometry.

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Predicting and Managing Surgical Intervention in Craniofacial Disharmony – a Biomechanical Perspective

Stephen Richmond, Liliana Beldie, Yongtao Lu, John Middleton, Brian Walker, Andrew Cronin, Nicholas Drage, Alexei Zhurov, and Caroline Wilkinson

INTRODUCTION

Predicting the outcome of orthognathic surgery is challenging in that the hard and soft tissues changes in the face require simulation, and these changes are dependent on the surgeon being able to carry out the surgical plan within an overall mean surface error of less than 2 mm.¹ The period of treatment is often in excess of 2 years, during which the individual's face is continually maturing. The facial contours continue to change after surgery as the facial swelling reduces.² Therefore simulation of facial changes should ideally reflect a combination of maturation and surgical change.

As a result of the long treatment duration, individuals are subject to changes in fashion – clothes, hairstyles, and cosmetic influences – and it is important when evaluating facial change that these factors are minimized. Another challenge is the reproducibility of color images. The quality of these depends on many factors, such as ambient light/lighting, ambient room temperature, quality of the lenses, film, or digital capture screens, as well as changes to surface facial topography and its interaction (lines of light incidence and reflection) with the aforementioned factors. Therefore, it is important also to evaluate the surface changes using standardized conditions.

The use of three-dimensional (3D) imaging has enabled valid and accurate capture of the facial contours, enabling the superimposition of a photorealistic texture in static and dynamic modes. This is an important advancement in evaluating surgical change as we can see change in soft tissues as a result of movement relative to a standardized framework and origin. We consider this to be a more valid measure of assessment of surgical change compared with static images as we see differences as a result of function, and this function is less likely to be influenced by awkward posing by individuals.

Both orthodontists and maxillofacial surgeons have sought to develop methods to predict surgical change in individuals with craniofacial disharmony using lateral cephalograms,³ photographs,⁴ video-imaging,⁵ and multivariate analyses.⁶ However, in spite of efforts to provide a detailed predictive plan, the outcome often falls short of reality.⁷

These errors may be minimized by:

- A full characterization of the facial features. Each face contains subtle differences that make the appearance unique, and it is important to characterize these features. For example, the lips may show significant variation in lip morphology (Figure 11.1).
- Taking into account detail of the relationship of the various soft tissues to the underlying skeletal structures. The relationship of soft tissues to underlying skeletal structures is widely variable, and this is highlighted by a significant amount of soft tissue being present anterior to the maxilla compared with the mandible (Figure 11.2).

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Figure 11.1 The lip morphology of these two individuals is different. (Left) The upper lip is well defined with a sharp cupid's bow, and the lower lip is edged with a rolled border. (Right) The cupid's bow is not well defined, with two halves clearly seen. There is a ridge 3 mm above and mimicking the vermilion border. The lower lip is everted, with a deep horizontal indent in the midline below the vermilion border. Similar amounts of skeletal surgical movement will result in differences in soft tissue changes as the lips have significant morphologic differences. (Screen images copyright Geomagic, Incorporated. Used with permission. All rights reserved.)

Figure 11.2 The relationship of the soft tissues (yellow) to the underlying skeletal structure. The images are taken from a cone beam computed tomography scan highlighting the complexity of the relationship of the upper and lower lips to the anterior part of the maxilla, the mandible, and each other. This picture has been created using AMIRA – a system for advanced visual data analysis (see <http://www.amira.com/>).

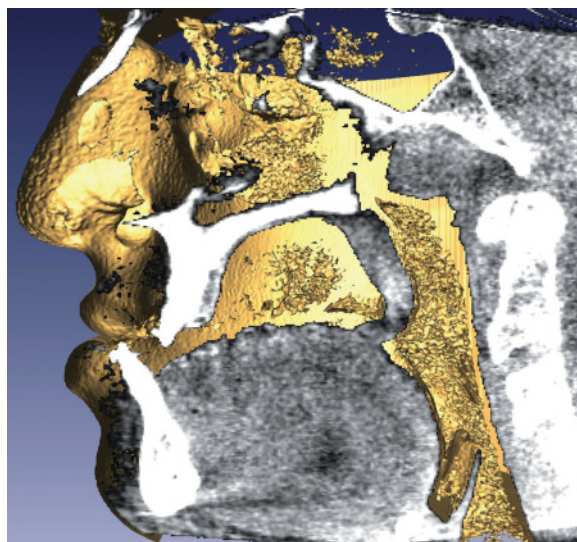


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Figure 11.3 Assessment of asymmetry. The individual shows asymmetry in the skeletal and soft tissue, with the left eye inferiorly placed in comparison to the right eye. The mandibular centerline is also to the left. (Screen images copyright Geomagic, Incorporated. Used with permission. All rights reserved.)

- Carrying out a full assessment of horizontal and vertical asymmetry. The assessment of asymmetry should be taken with respect to the individual's natural head posture. Figure 11.3 shows a vertical discrepancy between the left and right eyes, and a horizontal discrepancy with the mandibular centerline 6 mm to the left.
- An appreciation that the face moves during function (Figure 11.4).^{8–10} Previous publications have concentrated on the static imaging of individuals with craniofacial disharmony, but recent advances have facilitated 3D dynamic capture of the facial soft tissues. This enables an evaluation of soft tissue movements prior to and after surgical interventions.^{8–10} An individual's face changes during function. This is illustrated particularly during speech. When at rest, the upper lip shows good length. However, during the utterance of “pup” in the word “puppy,” the upper lip appears much shorter – the soft tissue profile changes are illustrated in Figure 11.4 using green surface markings. Ideally, functional movements should be utilized to simulate surgery for surgeons to plan procedures and for patients to understand and appreciate the likely surgical outcomes.
- Appreciating that each person is different, with a unique facial morphology, and as a consequence soft tissues will react differently depending on the detail of surgery planned (see Chapter 13).
- Mimicking the biologic structures using accurate biomechanical models. It is important to develop techniques that will accurately represent the biologic materials that make up the craniofacial complex.^{11–14}

SURGICAL PLANNING

The individual illustrated in Figure 11.5 attended the clinic expressing an interest in improving his facial appearance and reducing the prominence of his chin. Prior to surgery, full records were taken: facial

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Figure 11.4 Assessment of the bilabial movement of an individual saying the syllable “pup” in “puppy.” Note the upper lip at rest (left) and when saying “pup” (right). (Screen images copyright Geomagic, Incorporated. Used with permission. All rights reserved.)

photographs, cone beam computed tomography (CBCT) of the jaws, upper and lower dental impressions, and static and dynamic 3D laser surface images (Konica Minolta VIVID 910 and 3dMD, respectively; Konica Minolta Sensing Inc, Osaka, Japan). The laser surface scans were superimposed as best-fit onto the CBCT 3D construction of the skin surface. As CBCT and laser scans are not taken at the same time, there is always some degree of error in fit, usually less than 0.5 mm, due to some degree of facial posturing. The CBCT 3D reconstruction was adjusted to highlight the detail of the facial skeleton.

The sequence of procedures is outlined in Figure 11.5. With the surface scan and skeletal structures in the correct spatial relationship, these were then aligned to the horizontal plane based on the inner canthi and mid-sagittal planes (the origin being the mid-inner canthal point). To determine the soft tissue discrepancies, the average facial template (matched for gender and age) was fitted to the individual's face. The superimposition clearly identifies a midface insufficiency, and this can be quantified using a color deviation map. The midface is deficient by 4.9–5.3 mm. The lower face height is also increased by 4 mm. The “cut-away” approach was used whereby half the facial shell was removed to reveal the underlying skeletal structure.

A Le Fort type I osteotomy was performed, with the maxilla being moved upward by 4 mm and forward by 5 mm. The lower dental cast was scanned in the best-fit position to the upper dental cast, and the combined scans were best fitted to the denture of the CBCT with an accuracy of less than 0.3 mm. A sagittal split was performed on the mandible, and the CBCT of the lower denture was aligned to the lower dental cast by best-fit technique. This enabled the mandible to achieve the best possible fit with the maxilla.

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Figure 11.5 Surgical procedure sequenced and assessment of outcome using color maps. (Screen images copyright Geomagic, Incorporated. Used with permission. All rights reserved.)

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Figure 11.5 *(Continued)*

ASSESSMENT OF FACIAL MOVEMENT

Using dynamic motion capture cameras, the individual was captured at rest and saying the word “puppy” prior to surgery and at 3- and 6-monthly intervals. The sequence of images clearly illustrates the facial features at rest and in function (Figure 11.6).

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Figure 11.6 Individual facial sequences before surgery (left), 3 months after surgery (middle), and 6 months after surgery (right). The individual is shown at rest (top row) and at the same point saying “pup” in the word “puppy.” The shape of the profile before surgery (green) and 3 months afterward (orange) are outlined. The dotted green outline (bottom left image) is the rest position superimposed onto the functional position. (Screen images copyright Geomagic, Incorporated. Used with permission. All rights reserved.)

BIOMECHANICAL MODELING AND SURGICAL PREDICTION

Various methods have been developed with the purpose of utilizing finite element modeling as a prediction tool for surgery procedures and facial expressions. Back in 1996, Koch and co-workers simulated facial surgery by modeling the facial surface connected to the skull with springs, which implies that the model lacked the true volumetric physics.¹¹ More recently, they proposed a true volumetric finite element model for the facial surgery simulation, with the capability of incorporating incompressibility.¹² However, this model was restricted to the linear elasticity theory, which cannot deal with large deformations.

In 2003, Gladilin and co-workers proposed a nonlinear elastic approximation of facial tissue, and a comparison was made between the linear and nonlinear formulation, with the conclusion that, in case of large deformations, the linear elastic model proved unsuitable.¹³ One of the drawbacks of this facial model is the way in which the muscles are represented, which offers limited options for applying anatomically correct connections between muscles, and between muscles and the underlying skeleton.

With the improved imaging techniques for recording magnetic resonance imaging and CT data, and the availability of more refined software tools for transforming images into finite element models, more opportunities have arisen for computer-aided facial modeling.¹⁵ The work presented involves the use of patient-specific imaging data of the facial bone structure and facial surface combined with adjusted generic facial muscles. The facial simulation model is presently showing capabilities for mimicking surgical procedures and facial expressions. The final goal is to create and use the patient-specific finite element model for the planning of maxillofacial surgery, together with prediction of the results in terms of facial appearance after surgery. Several software packages have been used, namely Simpleware Software (Simpleware, Exeter, Devon, UK) and the Oasys LS-DYNA[®] Environment Package (Ove Arup, Solihull, West Midlands, UK) for the model build and LS-DYNAR for the finite element analysis.^{15–18} Several stages are involved in creating the finite element model and simulations, as described below.

Individual soft and hard tissues

For the example outlined here, the patient-specific data for the skull and outer face shell were used, while for the muscles, the data came from a standardized forensic database.¹⁹ The muscles were placed in the approximate anatomic positions outlined, employing techniques routinely used in forensic science. Each muscle was fashioned separately and stored as an .stl file (Figure 11.7).

Rapidform software (INUS Technology, Inc, Seoul, South Korea) was used to process the raw data.²⁰ The dense point clouds were cleaned. Holes were filled in, and sharp edges were smoothed using standardized algorithms. Nonuniform rational basis splines surfaces were employed to mathematically represent the exterior anatomic structures (Figure 11.8).

Modeling stage

A finite element model was created using ScanCAD, ScanIP, and ScanFE, which are modules of the Simpleware software package.¹⁵ The ScanCAD module, mainly used for working with implants, allows the importing of computer-aided design (CAD) models, positions them interactively within the image data already opened and generates a ScanIP mask of the combined data. ScanIP image processing soft-

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Figure 11.7 A soft tissue model structure was created for the facial muscles. (Screen images copyright Geomagic, Incorporated. Used with permission. All rights reserved.)

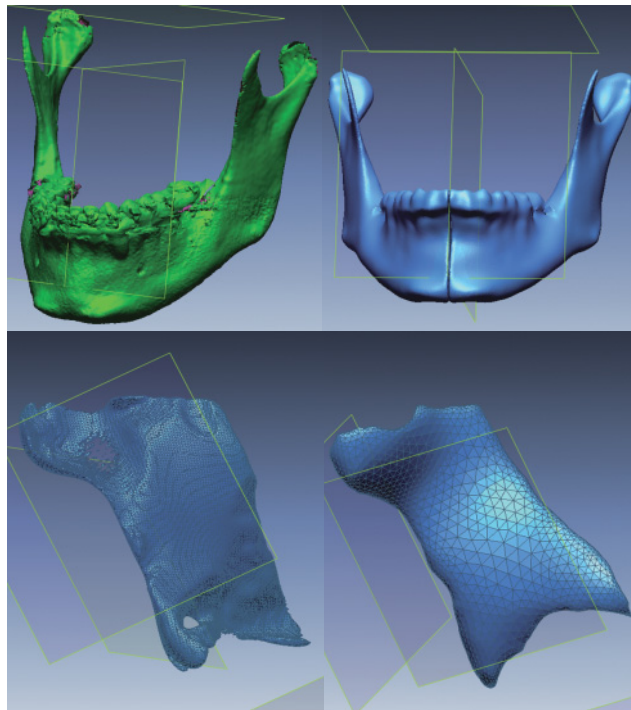


Figure 11.8 The .stl files were cleaned, and the holes filled in and smoothed. Nonuniform rational basis splines surfaces were used to represent the anatomy of the soft and hard tissues – mandible (top) and left masseter (bottom). (With permission from Rapidform® 3D scanning software.)

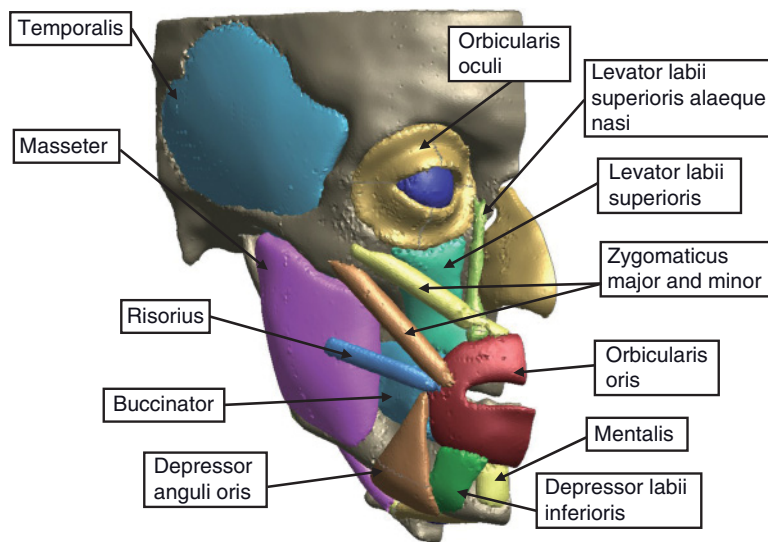


Figure 11.9 Finite element face model – muscles modeled. (From Oasys® PRIMER9.3 & D3PLOT User Manual, Ove Arup & Partners Ltd, 2008.)

ware provides an extensive selection of image-processing tools to assist the user in visualizing and segmenting regions of interest from any volumetric 3D data (e.g., magnetic resonance imaging, CT, or microCT). Segmented images can be exported as .stl files for CAD analysis and rapid prototyping manufacturing. The ScanFE module generates volume and/or surface meshes, contact surfaces, and material properties from segmented data.

By running the data through the various Simpleware modules, the finite element model of the face, including skeletal and soft tissues, was created. The assumption of face symmetry was made to allow working with a half-face model. This reduced both the size of the finite element model and also the simulation run-time. The finite element facial model consists of 24 facial muscles for one side, connected to the skull, to each other, and to the subcutaneous fat tissue (Figures 11.9 and 11.10). The connections were implemented based on the anatomic reality of the human face, as per the literature and consultations with anatomy experts from Cardiff University, UK. The final finite element model of the half face was meshed with approximately 2 million tetrahedral solid elements (Figure 11.11). For the pre-processing, Oasys PRIMER 9.3 was used to set up the final model with the connections, joints, symmetry boundary conditions, etc. Oasys D3PLOT 9.3 was used for postprocessing, such as visualization of the results, animations, viewing the displacements stresses, and so on.

Creating and implementing a constitutive muscle model

In order for the finite element simulation to produce reliable results, the use of an accurate constitutive model of the muscles is crucial. Although LS-DYNA offers a wide range of nonlinear constitutive models, the muscle model needs to have a capability for activation, to mimic the way muscles work in reality, that is, contracting when stimulated by electric signals received from the brain.

The constitutive muscle model was implemented as a user-defined subroutine and is based on the three-element Hill model, consisting of a parallel element, a serial element, and a contractile element.²¹

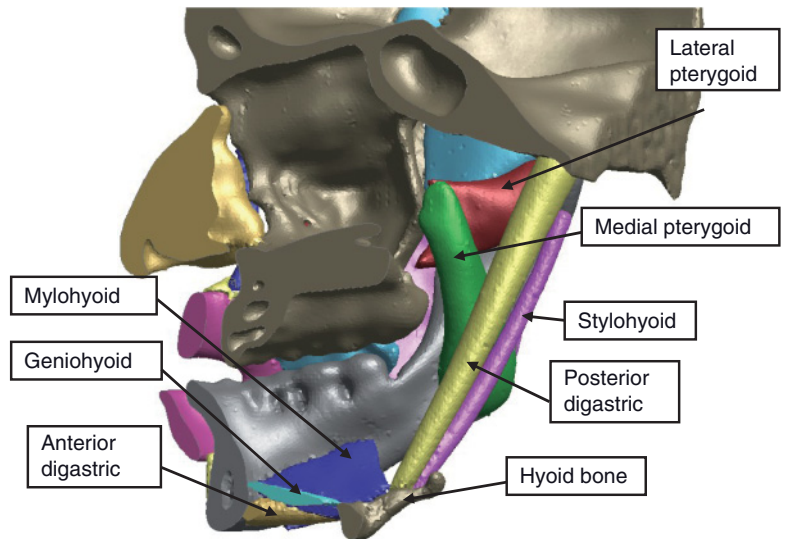


Figure 11.10 Finite element face model – muscles modeled. (From Oasys® PRIMER9.3 & D3PLOT User Manual, Ove Arup & Partners Ltd, 2008.)

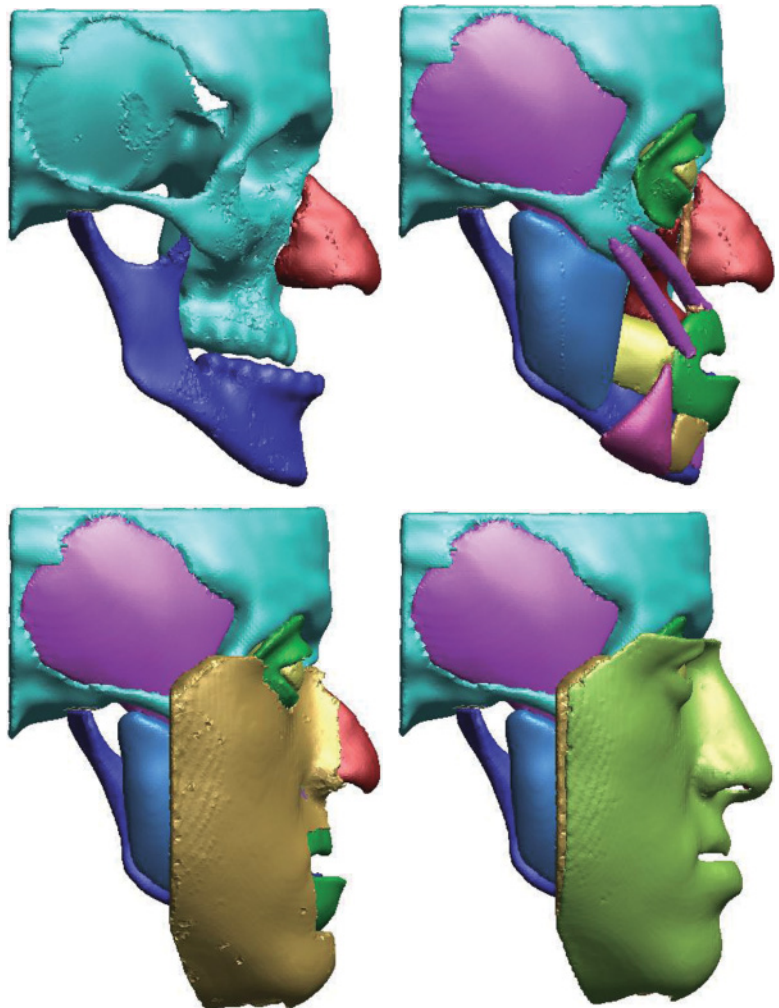


Figure 11.11 Finite element face model. The sequence illustrates the steps for the full-face build-up: skeleton and nasal cartilage (top left), placement of muscles (top right), fascia layer (bottom left), and facial skin surface (bottom right). (From Oasys® PRIMER9.3 & D3PLOT User Manual, Ove Arup & Partners Ltd, 2008.)

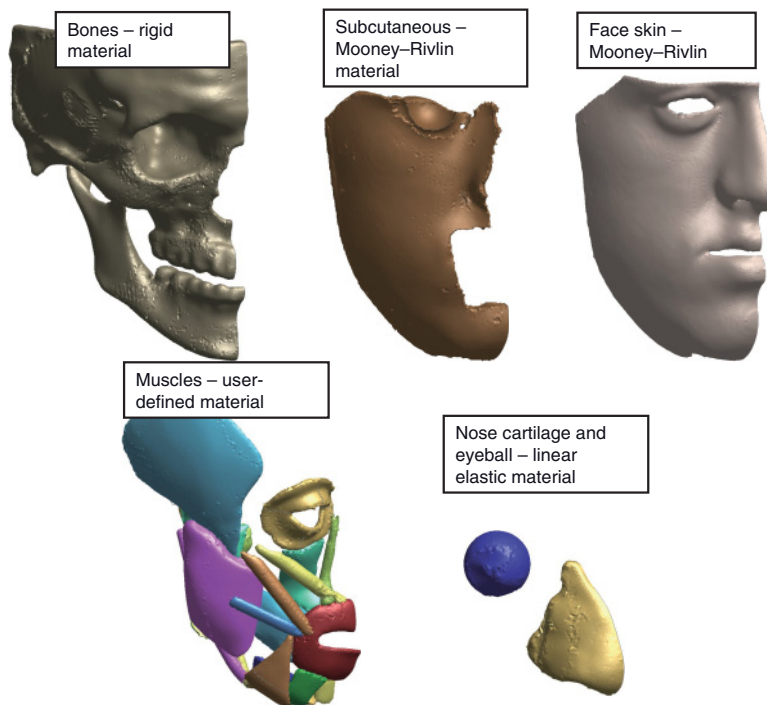


Figure 11.12 Materials used for the finite element model of the face. (From Oasys® PRIMER9.3 & D3PLOT User Manual, Ove Arup & Partners Ltd, 2008.)

This three-element model has been extensively used as a starting point in the past, one of the most advanced formulations to use it being that of Martins and co-workers.²² However, Martins' model is based on a contractile strain history, which is determined by performing costly static and dynamic optimization analyses. The model proposed here overcomes this shortcoming by incorporating the activation function into the fiber part of Martins' model and thus avoiding the usage of the contractile strain history.

The proposed constitutive muscle model is described by an active, quasi-incompressible, fibre-enforced, and hyperelastic formulation with the capability of simulating both active and passive behavior. An extensive literature search was conducted to gather the parameters necessary for building the muscle model. The validation of the constitutive muscle model was undertaken using test data from the literature.^{23–25} This was to allow for valid information regarding the stresses and strains in the muscles due to facial movement or facial surgery. Furthermore, using an accurate muscle model ensures a more accurate prediction for the outcome of surgery.

The rest of the finite element model components, such as the skull, nose cartilage, eyeball, face skin, and subcutaneous fat, were modelled using standard LS-DYNA materials (Figure 11.12).

Finite element simulations: maxillofacial surgery

Finite element analysis was performed to simulate the surgical procedures (Figure 11.13). This consisted of, first, a Le Fort type I osteotomy of the maxilla with movement 4mm upward and 5mm forward, and,

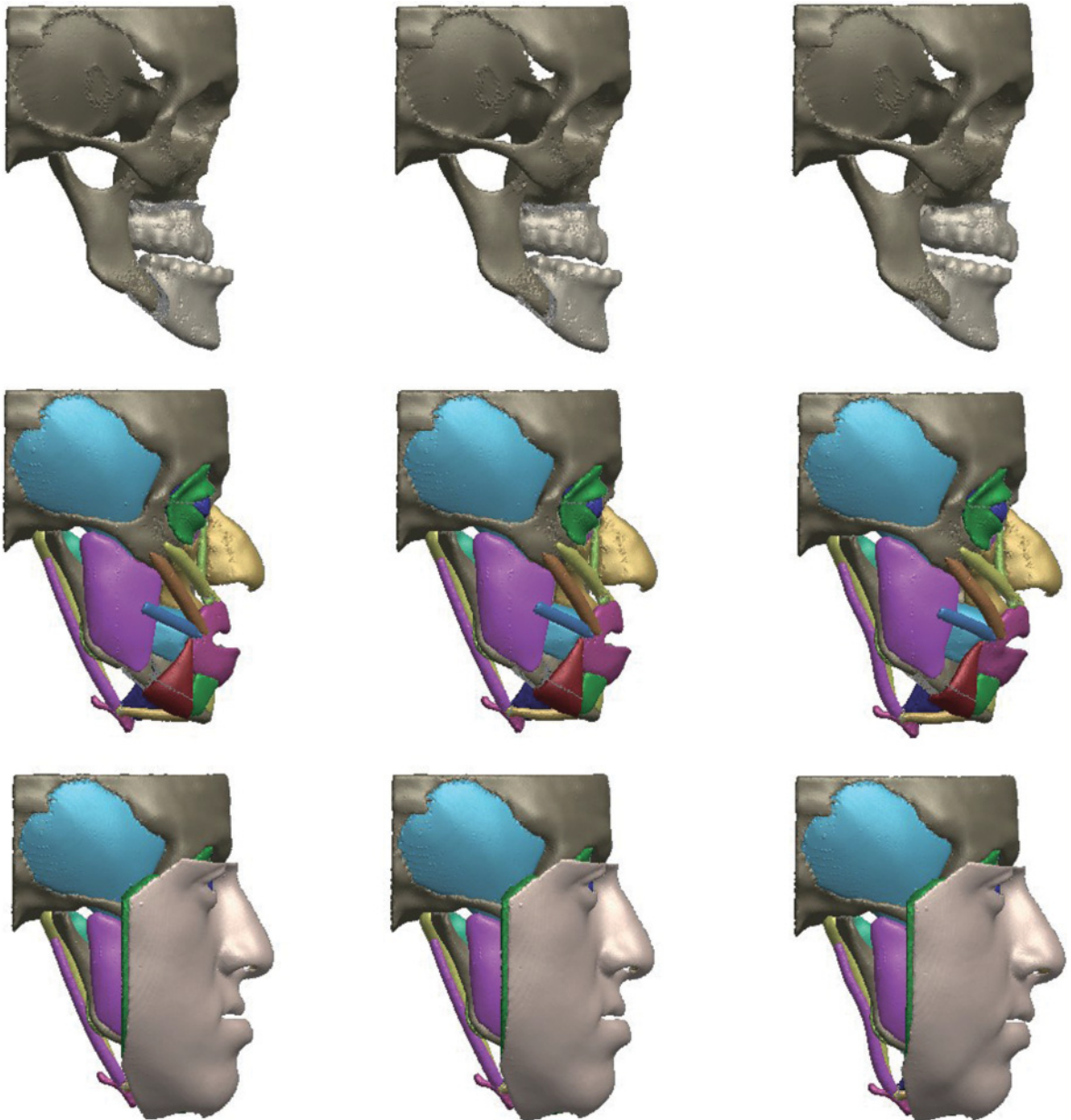


Figure 11.13 Finite element simulation of surgery. The left column shows the facial features before surgery. The middle column shows the facial features in the middle of the simulation. The right column shows the facial features after the surgery. (From Oasys® PRIMER9.3 & D3PLOT User Manual, Ove Arup & Partners Ltd, 2008.)

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Figure 11.14 Superimposition of facial finite element simulation with patient data at 3 (left) and 6 (right) months after surgery. The green represents a tolerance level of less than 1 mm. (Screen images copyright Geomagic, Incorporated. Used with permission. All rights reserved.)

second, a sagittal split osteotomy of the mandible and a movement of 4 mm upward and 8 mm posteriorly. This was done following the pre-treatment plan and confirmation from the surgeon who performed the actual surgery.

Post-surgical outcome assessments

The finite element result of the face after the maxillofacial surgery simulation was superimposed on the patient data at 3 and 6 months post-surgery, respectively, using Geomagic Qualify 10 (Geomagic, Inc, Research Triangle Park, NC, USA). The differences can be highlighted with a color deviation map (Figure 11.14). The comparison shows that the finite element prediction of the face after surgery is in good agreement with the actual patient results, with small areas less prominent in the lower part of the face (blue) and a narrow region of prominence on the bridge of the nose (yellow). The greatest discrepancy occurs in the lower region. The position of the lower lip at rest preoperatively is dependent on the type and amount of soft tissue anterior to the maxilla and mandible and the interaction of the lips, and this complexity was highlighted for this individual in Figure 11.2.

Finite element simulations: facial expression simulations

The constitutive muscle model was further used in the half-face model to simulate facial expressions such as the expression of “disgust” and “smile.” For the expression of “disgust,” the muscles activated were levator labii superioris alaeque nasi, orbicularis oculi, and depressor anguli oris (Figure 11.15). For the “smile,” the muscles activated were the zygomaticus major, zygomaticus minor, and orbicularis oculi (Figure 11.16).

Furthermore, the lowering of the mandible was also simulated by contracting the anterior belly of the digastric muscle. This work is still at an early stage with the intention of fully simulating speech.

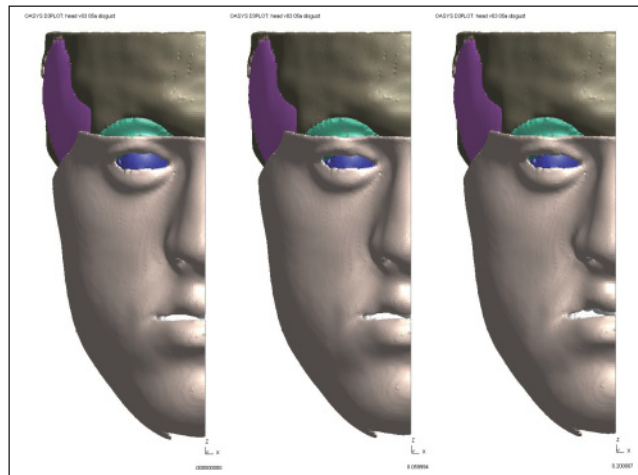


Figure 11.15 Facial expression – disgust. This was simulated by activating the levator labii superioris alaeque nasi muscle, the orbicularis oculi muscle, and the depressor anguli oris muscle simultaneously. At the beginning (left), during facial action (middle), and fully activated (right). (From Oasys® PRIMER9.3 & D3PLOT User Manual, Ove Arup & Partners Ltd, 2008.)

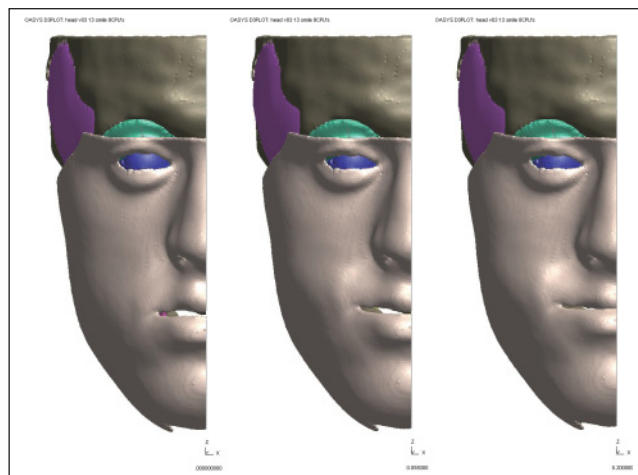


Figure 11.16 Facial expression – smile. This was simulated by activating the orbicularis oculi muscle, the zygomaticus minor muscle, and the zygomaticus major muscle simultaneously. Beginning (left), during facial action (middle) and fully activated (right). (From Oasys® PRIMER9.3 & D3PLOT User Manual, Ove Arup & Partners Ltd, 2008.)

CONCLUSION

Using the techniques described here, it is possible to individualize and mathematically model the soft and hard tissues to facilitate the prediction of hard and soft tissues as planned prior to operation. The challenge is to refine the techniques for routine use and to simulate speech and other facial actions.

Please refer to the supporting companion website at: www.wiley.com/go/kau

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12

Understanding the Facial Changes Associated with Postoperative Swelling in Patients Following Orthognathic Surgery

Chung How Kau, Stephen Richmond, and Andrew Cronin

INTRODUCTION

Advancements in three-dimensional (3D) technology have accelerated at a tremendous pace over the last two decades, with newer machines and software support appearing rapidly in the marketplace. This now means that applications for the clinical settings can be created and used in routine diagnosis, treatment planning, and patient education.

Broadly, 3D imaging devices may be classified as internal soft and hard tissue devices or external surface scanners. Internal imaging devices consist of 3D conventional and cone beam computed tomography scanners,¹⁻³ magnetic resonance imagers and ultrasound devices. These provide a large amount of clinical data but are radiation dose-intensive and often costly. External surface scanners tend to be less invasive and less expensive to use. These include light-based scanners, moiré fringe techniques,^{4,5} laser scanning,⁶⁻¹¹ and stereo-photogrammetry.^{12,13}

Due to the advantages of surface acquisition systems, many early studies tended to favor the use of external surface scanners. The variety of applications with these 3D devices has resulted in a better understanding of the craniofacial form. In recent times, 3D images have been created to establish databases for normative populations,¹⁴ facial averages,¹⁵ and cross-sectional growth changes,^{16,17} as well as for assessing clinical outcomes in surgical¹⁸⁻²⁴ and non-surgical²⁵⁻²⁷ treatments in the craniofacial region.

One area of interest to head and neck clinicians, which include plastic surgeons, oral and maxillofacial surgeons, and orthodontists, is the study of soft tissue changes associated with orthognathic surgery. The traditional method of understanding post-operative soft tissue changes was to plot linear measurements on landmark-based points.²⁸ Other newer methods have compared treatment changes

between groups of normal adults and those with facial disproportion²⁹ by comparing the color codes on facial deviation maps. More recently studies have also compared facial asymmetry before and after surgery.³⁰

3D surface imaging has proven to be an effective tool in the study of facial morphology. The 3D images are obtained by laser triangulation when a distortion of the light pattern falls on the surface of a subject. The scanning process is noninvasive and normally completed within a few seconds. Previous studies have reported on the validity and accuracy of the commercially available Minolta scanners and found them to be highly accurate.^{10,31–33} Furthermore, 3D soft tissue capture is reliable and reproducible.³⁴

The application of 3D surface imaging to the understanding of facial swelling can result in answers that provide clinical information to both patient and clinician.

APPLICATION OF SURFACE IMAGING

This section describes the usefulness of 3D surface imaging for understanding facial swelling in a group of orthognathic post-operative subjects. Some of the information has previously been reported.³⁵

Subjects

12 subjects (seven males and five females) with a mean age of 28.5 years were studied. Each of the subjects required orthognathic surgery on either one or both jaws. Five patients presented with a Class II skeletal pattern and seven patients with a Class III pattern. Each patient received a routine drug regime that consisted of three doses of 1.3 g Augmentin and 8 mg Dexametasone, one dose at the induction of anesthesia and two other postoperative doses in the hospital during the recovery period. All subjects were discharged within 3–5 days following surgery.

Three-dimensional imaging system

The laser imaging scanning system previously described was used, only a brief introduction will be made here. The system consisted of two high-resolution Minolta VIVID VI900 3D (Konica Minolta Sensing, Inc, Osaka, Japan) cameras, with a reported manufacturing accuracy of 0.3 mm, operating as a stereo-pair. Each of these cameras emits an eye-safe Class I laser (US Food and Drug Administration) of wavelength 690 nm at 30 mW with an object-to-scanner distance of 600–2500 mm and a fast-mode scan time of 0.3 seconds. The system uses a one-half-frame transfer charge-coupled device and can acquire 307,000 datapoints. The scanners were placed at a distance of 1350 mm from the head frame.

The scanners were controlled with multi-scan software (Cebas Computer GmbH, Eppelheim, Germany), and data coordinates were saved in a VIVID file format (.vvd). Information was transferred to a reverse modeling software package Rapidform 2006 PP2 (RF6; INUS Technology Inc, Seoul, Korea) for analysis. This software provides nine different 3D work activities together, which allow high-quality polygon meshes, accurate freeform nonuniform rational B-spline surfaces and geometrically perfect solid models to be created. RF6 generates data as absolute mean shell deviations, standard deviations of the errors during shell overlaps, maximum and minimum range maps, histogram plots, and color maps. All linear measurements are made in millimeters.

Data capture technique

A custom-built studio facilitated standardized light conditions. Natural head posture was adopted for this study, as this has been shown to be clinically reproducible.³⁷ The subjects sat on a self-adjustable stool and were asked to look into a mirror with standard horizontal and vertical lines simulating a cross marked on it. They were asked to level their eyes to the horizontal line, and the midline of the face was aligned to the vertical line. Adjustments to seating heights were made to assist the subjects in achieving natural head posture. The subjects were also instructed to swallow hard and to keep their jaws in a relaxed position just before the scans were taken. The total scan time was approximately 7.5 seconds.

Data processing of left and right facial scans

Extraneous data were removed by an in-house-developed software subroutine.³⁸ This automatic and systematic process further reduced the scanned images into shells and identified those small shells that represented minor scanning distortions. These images were smoothed out, while preserving all shape and volume, and the left and right scans were aligned to one another based on the areas of overlap of the faces. The pre-merged scans were carefully checked individually, and unwanted areas that could not be automatically removed were done so manually by dividing the unwanted areas from the main shell before proceeding to the next stage. Recorded in millimeters, the mean score for left and right scans gave an indication of the data reliability. Finally, one whole face was generated for each subject.

Facial analysis

3D laser scans were recorded over six time periods (T1 – presurgical scan; postoperatively: T2 – 1 day, T3 – 1 week, T4 – 1 month, T5 – 3 months, and T6 – 6 months). To facilitate the study of surface changes associated with facial swelling after surgery, the surface scan recorded at the sixth month (T6) was used as the baseline to compare all the surface changes after surgery.

Each individual's surface scan for the time period was overlaid on the baseline by aligning five points on the facial scans (four points at the outer and inner canthus of the eyes and one point on the nasal tip). The superimposition was finalized by using the iterative closest point or best-fit algorithm built into RF6.³⁹ The shell-to-shell deviation was measured on a sliding color scale that displayed the mean shell deviations and percentage changes corresponding to the deviation in facial contours between each time point.

To determine facial changes resulting from treatment, the mean shell deviation for each pair of overlapped faces was recorded. This gave an estimate correlating the differences associated with facial swelling. Furthermore, a previously known value of 0.85 mm was applied to each set of shell deviations.⁴⁰ The percentage not corresponding to this value was recorded as the percentage deviation from treatment changes and facial swelling after surgery (Figure 12.1). This method of studying the percentage change in facial swelling has been validated and reported.³⁹

RESULTS

The results were recorded in millimeters and percentage changes. Figures 12.2 and 12.3 indicate the swelling changes for single-jaw and double-jaw surgeries, respectively.

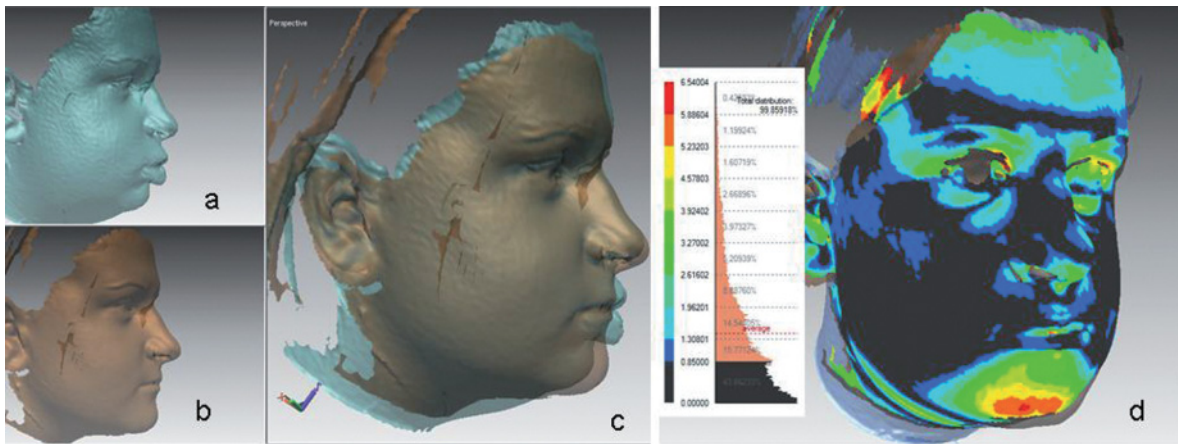


Figure 12.1 (a) Day 1 facial scan. (b) Six month facial scan. (c) Superimposition of the scans according to the technique. (d) Color map indicating areas of differences at a tolerance of 0.85 mm. (With permission from Rapidform® 3D scanning software.)

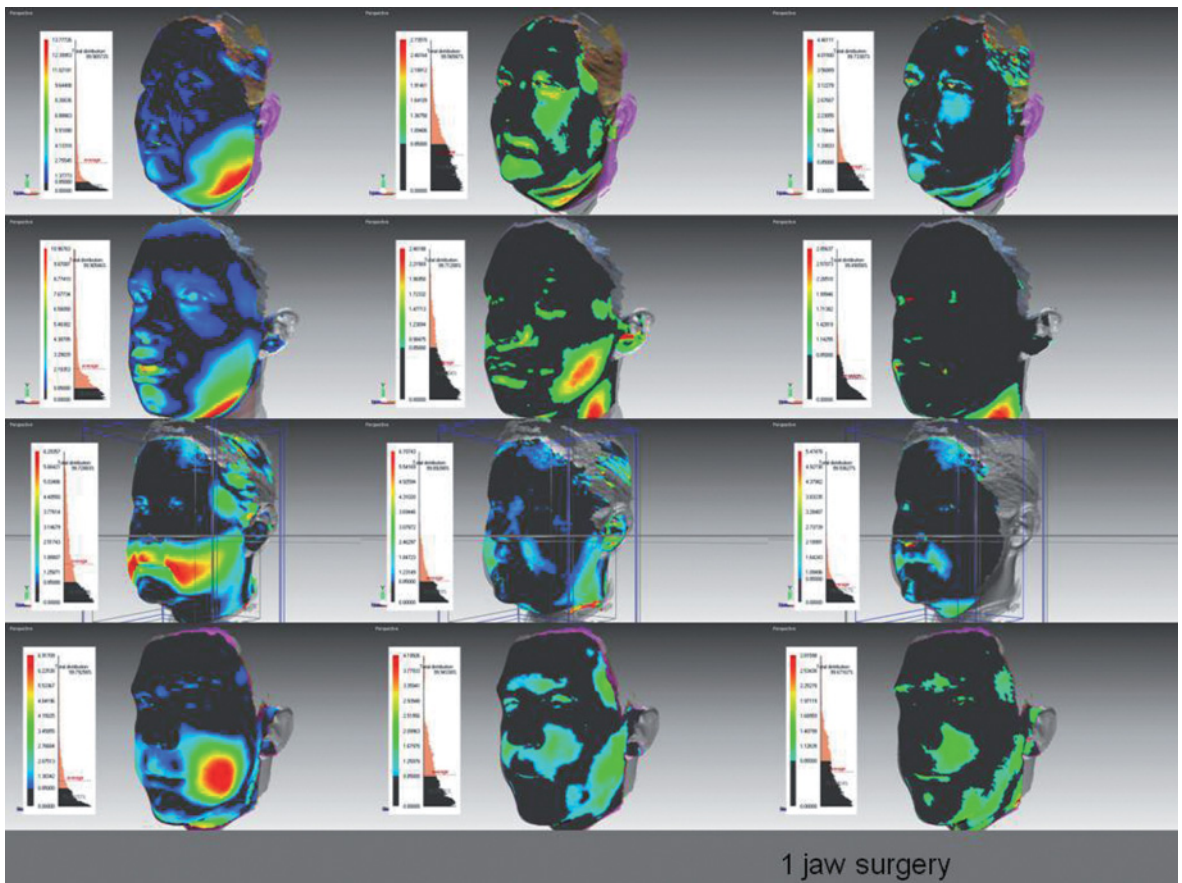


Figure 12.2 Composite color maps of four patients who had undergone a single-jaw procedure. (With permission from Rapidform® 3D scanning software.)

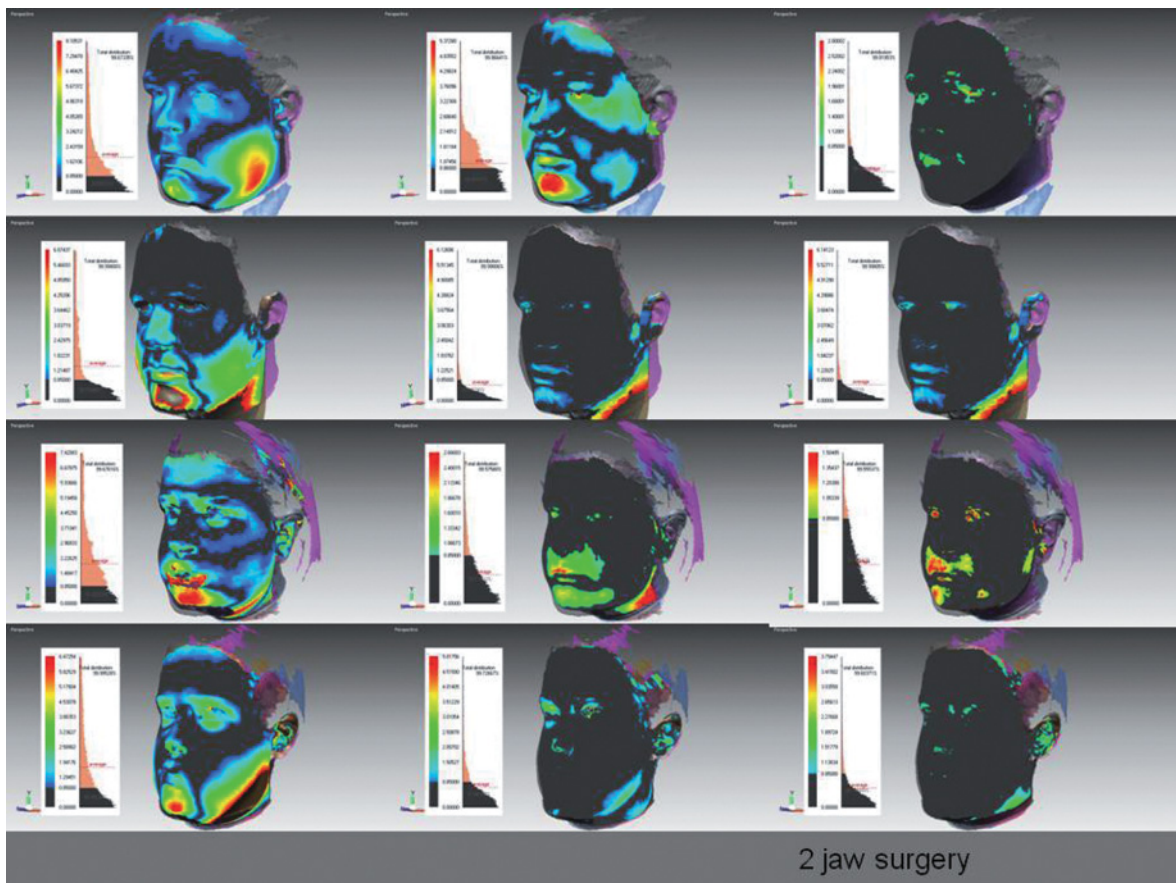


Figure 12.3 Composite color maps of four patients who had undergone a double-jaw procedure. (With permission from Rapidform® 3D scanning software.)

Facial swelling changes

The mean shell deviations between pairs of whole faces were recorded, showing a decrease in mean scores over time. The mean scores at T2 versus T6 were 1.30 mm and 1.63 mm for single- and double-jaw surgery, respectively. These scores were reduced to 0.64 mm and 0.50 mm after 6 months. There seems to be a faster rate of decrease in scores for double-jaw surgery versus single-jaw surgery.

In the analysis of the percentage changes, as illustrated on the color scale, the amount of facial swelling was greatest on the first day following surgery. This corresponded to a percentage change from baseline of 52.3% for single-jaw surgery patients and 63.8% for bimaxillary surgery patients. The areas where the majority of the postoperative swelling occurred corresponded predicted with location of the surgical treatment.

Facial swelling reduced substantially within the subsequent months following surgery, as illustrated in Figure 12.4. The amounts of swelling remaining at 1 month were 29.2% for single-jaw surgery and 24.2% for bimaxillary procedures. This improved further to 20.7% and 14.7%, respectively, at 3 months.

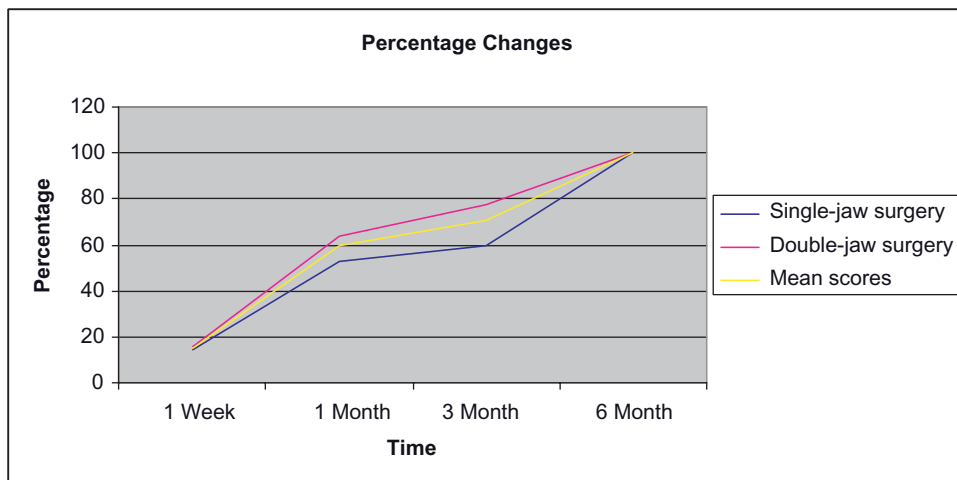


Figure 12.4 Graph showing improvements in facial swelling reduction for single-jaw, double-jaw, and mean percentage scores. The mean scores (yellow) represent the average of single- and double-jaw surgery. Approximately 60% of swelling decreases within 1 month of surgery and thereafter to 70% within 3 months.

Reduction in facial swelling

In determining the percentage reduction in facial swelling, the difference in facial deviation for each set of scans was calculated by subtracting the present amounts of swelling against the original amount of swelling present on the “first day” (T6–T2).³⁹ This value was further divided by the original “first-day” swelling value to give a percentage score quantifying the reduction in swelling.

The changes for each subject were recorded at each time period and the mean scores calculated. The improvements in facial swelling after 1 week, 1 month, and 3 months were recorded as 14.54%, 63.97%, and 59.87% for single-jaw patients, whereas the improvements for bimaxillary-jaw patients were 15.43%, 63.97%, and 77.18% for the same periods. The greatest reduction in swelling occurred within the first month following orthognathic surgery, and the mean percentage improvement was approximately 60% (Figure 12.4).

DISCUSSION

A significant amount of soft tissue change occurs following orthognathic surgery. Clinicians have conveyed the problems associated with facial swelling and its disproportion to patients during every routine case workup. Unfortunately, the exact nature of changes in soft tissue swelling has not been reported in great detail prior to this work.

A recent study did attempt to quantify the swelling changes following surgical removal of the mandibular third molars. 3D facial morphology from each subject was studied before and 2 days after surgery, and an attempt at quantifying volumetric changes was made. The results, however, were not conclusive about the reduction in postoperative swelling after surgery, although the authors managed to describe a range of absolute volume changes.¹¹

To date, clinicians have not been able to explain the changes in soft tissue associated with the inflammatory process, because the information is not present in the literature. The use of 3D technology in this study now provides an easy and efficient means to study facial swelling and to communicate the percentage facial changes to patients. This study evaluates the postoperative swelling following orthognathic surgery. Although the patient numbers are small in this sample, the number of image captures (1 day, 1 week, and 1 month postoperatively) represents 60 clinical recordings, a dataset unique in the literature.

Patients are often anxious to know the treatment effects following orthognathic surgery, but current information available has only been extrapolated from research using 2D data. Consequently, clinicians have not been able to provide the patient with an accurate picture or to give advice regarding the morbidity involved. The successful application of this technology provides a means for further analysis in clinical trials, which could include the types of surgical techniques performed and alteration of drug regimes. Finally, the imaging device used is a fast, noninvasive, and efficient method to capture 3D information on facial morphology.

CONCLUSION

The following conclusions may be drawn from this study. Noninvasive 3D surface imaging is a quick, efficient, and noninvasive method to capture facial morphology. The amount of swelling is greatest on day 1 after surgery but improves significantly with time. Bimaxillary-jaw surgery produces a greater amount of swelling, but this reduces at a faster rate than for single-jaw surgery. Approximately 60% of the initial swelling is reduced after 1 month for both single and bimaxillary orthognathic surgery.

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13

Visualizing Facial Growth

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Chung How Kau, and Frank Hartles*

INTRODUCTION

Clinicians are familiar with visualizing facial changes from longitudinal growth studies using sequential lateral cephalometric line drawings superimposed on the sella–nasion line at the sella. One of the fundamental challenges in assessing facial growth is to identify structures in the facial–skeletal framework that are unlikely to change or will undergo minimal change as a result of craniofacial development.

A radiograph is influenced by projection and interpretation errors, and researchers have focused on superimposition points identified on the midline landmarks. However, the radiographic identification of midline structures is far from easy, and consequently the resulting sequential radiograph superimpositions are subject to positional errors (vertical, anteroposterior, and rotational).^{1–4} The positional error is highlighted over the course of orthodontic treatment (18 months) with a significant increase in size in the frontal sinus associated with inferior placement of the nasion locator (Figure 13.1).

For ease of use, clinicians have been trained to apply superimposition techniques on the sella–nasion line registered at the sella for assessing treatment outcomes. Evidence informs us that both the sella and the nasion move until late adolescence, and the resulting registration of the radiographs on the point sella will result in the projection of the face downward and forward in the vast majority of cases, the minority of cases exhibiting vertical and backward rotations (Figure 13.2).³ Without a suitable reference structure, it is almost impossible to evaluate the influences of clinical interventions on craniofacial structures with a high degree of confidence.

With the questionable diagnostic value of lateral cephalograms associated with the known risks of exposure to radiation, a valid alternative is required for clinicians to determine the influence of clinical interventions on facial growth and the craniofacial complex on a routine basis. In addition, the meaningful effects of orthodontic care are often mostly visible through dental alignment and facial soft tissue harmony. There are many systems available to evaluate dental changes, but very few for facial soft tissues.⁵

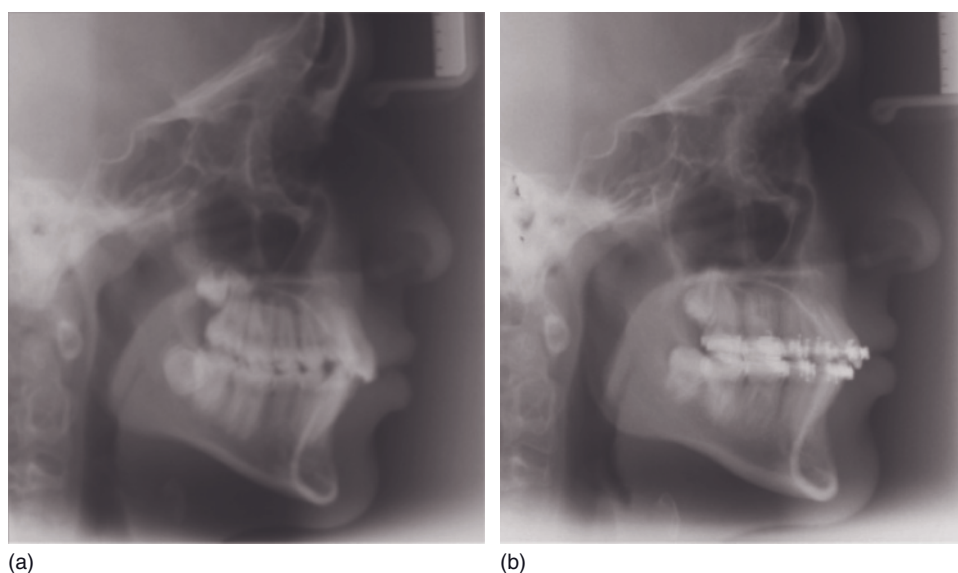


Figure 13.1 Change in skeletal structures during the course of orthodontic treatment. There has been a significant thickening of the frontal bone resulting in a displacement of the nasal locator downward. There have been small but significant changes in the cranial base, maxillary, and mandibular complexes that make registration difficult and inappropriate on the sella–nasion line.

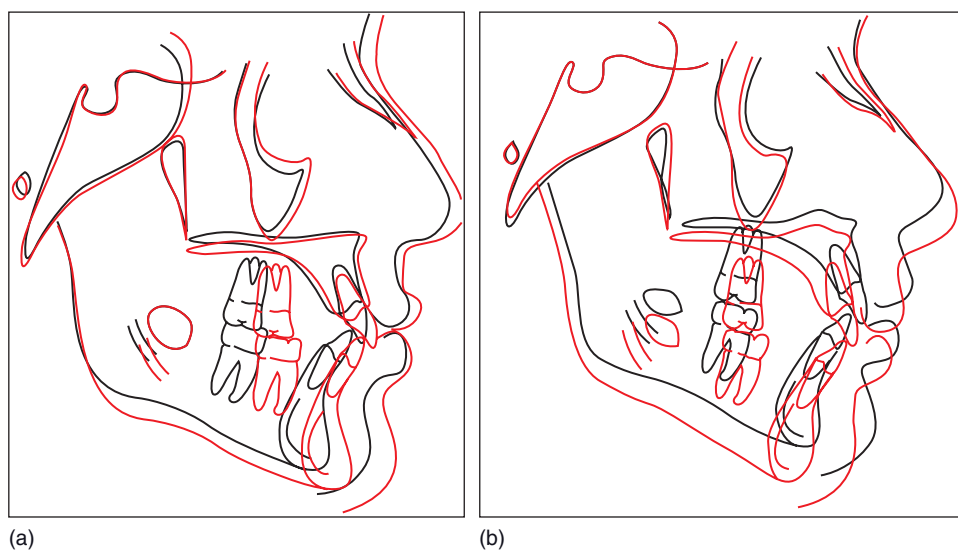


Figure 13.2 Pre- and post-treatment cephalometric tracings superimposed on the sella–nasion line at the sella, indicating a downward and forward movement (a; tracing of the radiographs in Figure 14.1) and a downward and backward movement (b).

STANDARDIZED REFERENCE FRAMEWORK

It has been only in the last 10 years that reasonably priced, readily available noninvasive three-dimensional (3D) surface scanning equipment has become available, facilitating the detailed accurate analysis of facial soft tissues for routine clinical practice. These systems can capture surface data in static and dynamic modes. The 3D facial data obtained still require the basic prerequisites to enable a valid sequential analysis of facial growth, that is, an origin and reference landmarks/planes (x - y , x - z , and z - y) that do not move or move least over time (Figure 13.3).

The landmarks that appear to move least are the inner canthi. Several reports have suggested that these points move posteriorly over time, although it is unclear whether these points actually move distally or are a function of the type of alignment used (e.g., best-fit or generalized Procrustes analyses) and their relative position in relation to other facial landmarks.^{6,7,8} There is a small increase (less than 2mm) in width between the inner canthi from 12 to 16 years old, generally the greatest increase in distance occurring between 10–18 months and 2–12 years of age.^{9,10} The inner canthi are often used as markers of facial dysmorphism.^{9,11}

To establish a reference framework, it is possible to align the facial shell to a transverse plane (x - z) passing through the inner canthi, and a sagittal plane (y - z) passing through the middle of the face, as outlined in Chapter 7.

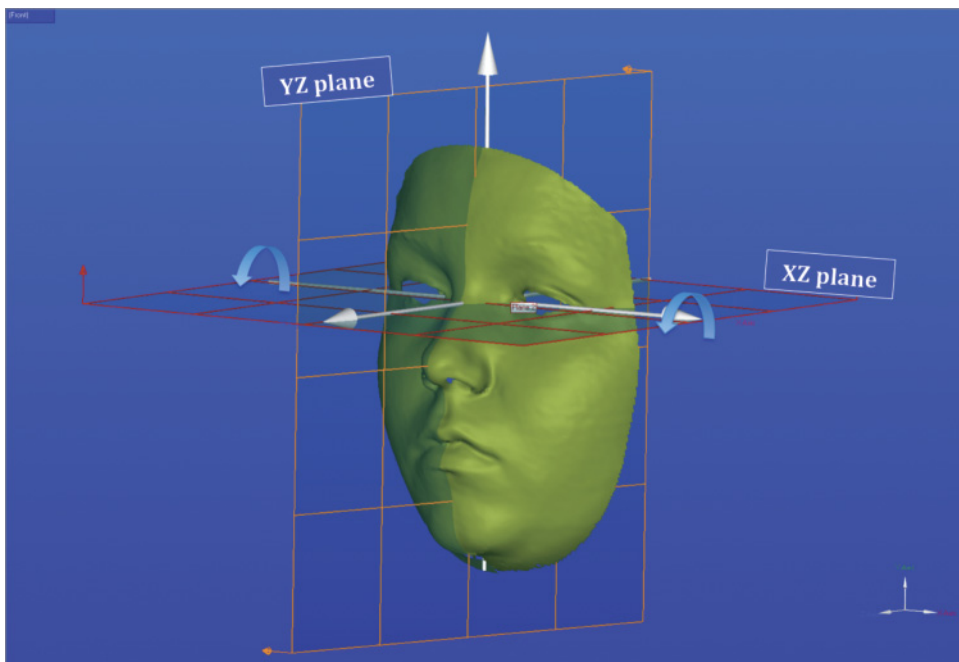


Figure 13.3 The face has been aligned to the inner canthal and sagittal planes. However, if the coronal plane is not set according to natural head posture, there will be a tendency for the face to rotate forward or backward on the x -axis through the inner canthi. (Geomagic Qualify; Geomagic, Inc., Research Triangle Park, NC, USA.)

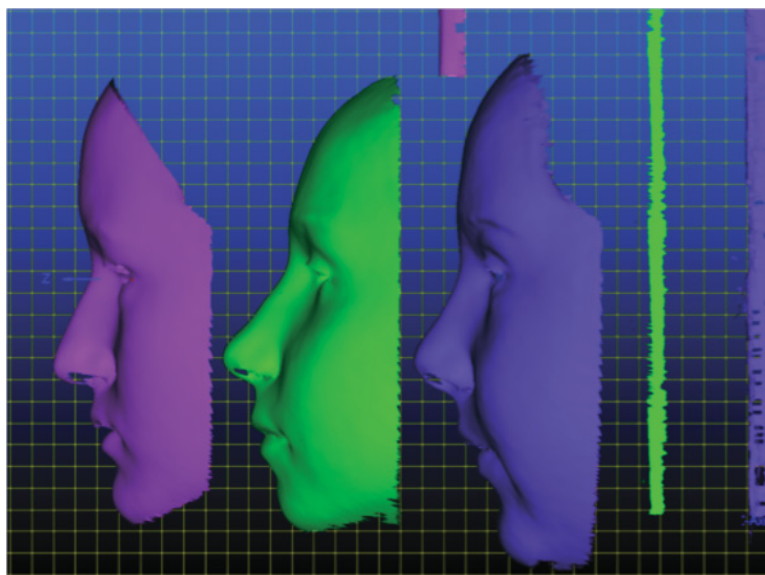


Figure 13.4 Three 12-year-old faces aligned to natural head posture and the inner canthi, indicating differences in positioning of the head, facial size, and shape. The vertical lines indicate the “true” vertical of the reference framework. The left facial shell shows an individual with a short flat face; the middle shell shows a more convex face with prominence of the lower face; the convex long face on the right shows less prominence of the lower facial third. The differences in face height and facial prominence exceed 15 mm (left compared with right). (Geomagic Qualify; Geomagic, Inc., Research Triangle Park, NC, USA.)

NATURAL HEAD POSTURE

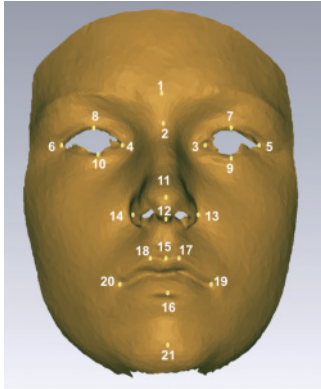
The face can, however, rotate about the x -axis, and the face will require a reference to the true vertical (Figure 13.3). The alignment to true vertical is necessary and determined by positioning the head using the technique of natural head posture (NHP). To reproduce the positioning of the head in space, it is necessary to reference the face to the true horizontal and vertical, and this can be achieved using a vertical and horizontal framework.

The NHP has been reported as highly reproducible.^{12,13} It must be remembered that not all individuals hold their heads in a similar posture. That is, different individuals may face straight forward or slightly upward or downward (Figure 13.4). It may be possible to create an average NHP to facilitate comparisons between individuals. However, growth changes are most likely to be valid when comparing changes in individuals with respect to their own NHPs.

FACIAL VARIATION

Clinicians have evaluated face shape and size using simple cephalometric assessments, such as the ANB points and maxillary–mandibular plane angles in association with facial proportions. 3D imaging provides the opportunity to reclassify facial morphology. Using 21 facial landmarks (Figure 13.5), it is

No.	Abbrev.	Name	Definition
1	G	Glabella	Most prominent midline point between the eyebrows
2	N	Nasion	Deepest point on nasal bridge
3	enL	Endocanthion	Left inner commissure of eye fissure
4	enR	Endocanthion	Right inner commissure of eye fissure
5	exL	Exocanthion	Left outer commissure of eye fissure
6	exR	Exocanthion	Right outer commissure of eye fissure
7	psL	Left palpebrale superius	Superior midportion of free margin of upper left eyelid
8	psR	Right palpebrale superius	Superior midportion of free margin of upper right eyelid
9	piL	Left palpebrale inferius	Inferior midportion of free margin of lower left eyelid
10	piR	Right palpebrale inferius	Inferior midportion of free margin of lower right eyelid
11	Pmn	Pronasale	Most protruded point of the apex nasi
12	Sn	Subnasale	Midpoint of angle at columella base
13	alL	Left alare	Most lateral point on left alar contour
14	alR	Right alare	Most lateral point on right alar contour
15	Ls	Labiale superius	Midpoint of the upper vermillion line
16	Li	Labiale inferius	Midpoint of the lower vermillion line
17	cphL	Left crista philtri	Point on the left elevated margin of the philtrum just above the vermillion line
18	cphR	Right crista philtri	Point on the right elevated margin of the philtrum just above the vermillion line
19	chL	Left cheilion	Point located at left labial commissure
20	chR	Right cheilion	Point located at right labial commissure
21	Pg	Pogonion	Most anterior midpoint of the chin.



(a)

(b)

Figure 13.5 Twenty-one soft tissue landmarks used to explore facial variation.

possible to highlight their spatial distribution in a population.¹⁴ Although 21 landmarks can be identified, certain landmarks are considered to be more reproducible than others (e.g., the inner canthi compared with exocanthi; see Table 7.1).^{15,16}

Three hundred and fifty 15-year-olds (184 males and 166 females) were recruited from the Avon Longitudinal Study of Parents and Children (ALSPAC). ALSPAC is a longitudinal birth cohort study of the determinants of development, health, and disease during childhood and beyond.¹⁷ The distribution of facial landmarks was explored using two methods of registration. In the first method, translation and rotation, and in the second uniform scaling, translation, and rotation, aligned the facial shells. Generalized Procrustes analysis¹⁸ was used to provide the best-fit of the landmarks only. The former approach is applied where both size and shape variations are equally important. The latter approach is used in morphometrics, where the focus is on shape variation only.^{18,19}

The landmark distributions about their centroids, obtained with the two methods of alignment, are depicted as sets of ellipsoids whose semi-axes are equal to the standard deviation of the landmark position in the x -, y -, and z -axis, respectively. The first distribution of points (yellow) clearly shows a significant vertical component around the eyes, lips, pronasale, and chin. When the points have been adjusted for size (height, width, and depth) using uniform scaling (blue), the distribution of points show less variation with small discrete clusters. The difference between the two plots is emphasized when they are superimposed (Figure 13.6). The midline points show greater variation in the y - and z -axes compared with the x -axis.

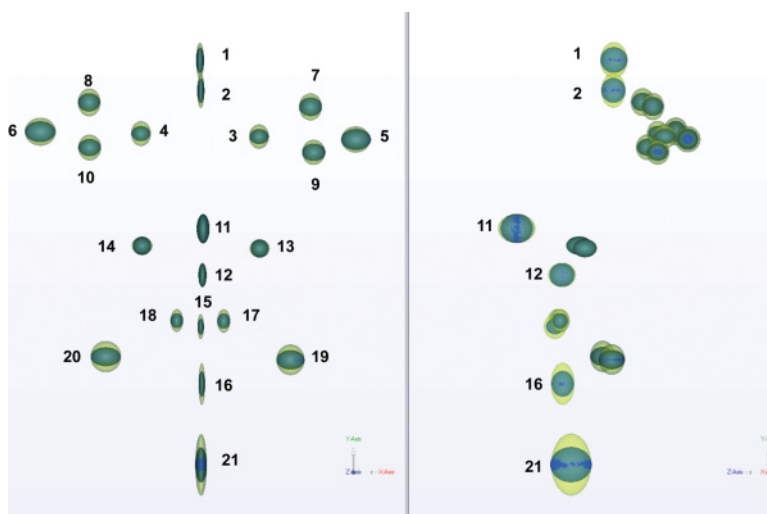


Figure 13.6 The distribution of facial landmarks about their centroids for 350 15-year-olds. The ellipsoids represent the standard deviations of the landmark position in the x -, y -, and z -axes for face alignment considering both size and shape (yellow) and shape only (blue). (Left) front view, and (right) lateral view.

Clearly, face height, width, and depth (size) are important in orthodontics as patients often present with particularly challenging malocclusions such as long and short faces. These face types have validity with genotype–facial phenotype associations.²⁰

ANALYSIS OF FACIAL VARIATION

The study of the unscaled data on 350 15-year-old children using principal component analysis¹⁸ identified three major components that explained 46.6% of the variation in face size and shape. The first principal component comprised 10 landmarks in the upper part of the face, including eight landmarks around the eyes (3–10), glabella (1), and nasion (2); and seven landmarks in the lower part of the face (15–21). All these landmarks were identified in the y -axis, with the upper part of the face being positive and the lower part negative, indicating that the upper and lower parts of the face move essentially together or apart, creating short or long faces. The first component explained 27.6% of the variance.

The second principal component involved landmarks around the eyes (3–10) principally in the x -axis, with the relationship that the left and right eyes move together or apart. This component explained 11.3% of the variance.

The third principal component involved landmarks associated with the nose (11–14) in the z -axis. This component explained 7.7% of the variance.

Using the centroids of the groups of landmarks, it was possible to demonstrate the effect on facial variation according to the three major principal components by plotting the variation from the mean in 0.5 banded increments up to over 2 standard deviations (SD) (Figure 13.7).

For the first principal component, we see a progression from a short, wide flat face (–2 SD) to a long thin face (+2 SD). The distance between the upper and lower facial centroids ranged from 62.6 mm to

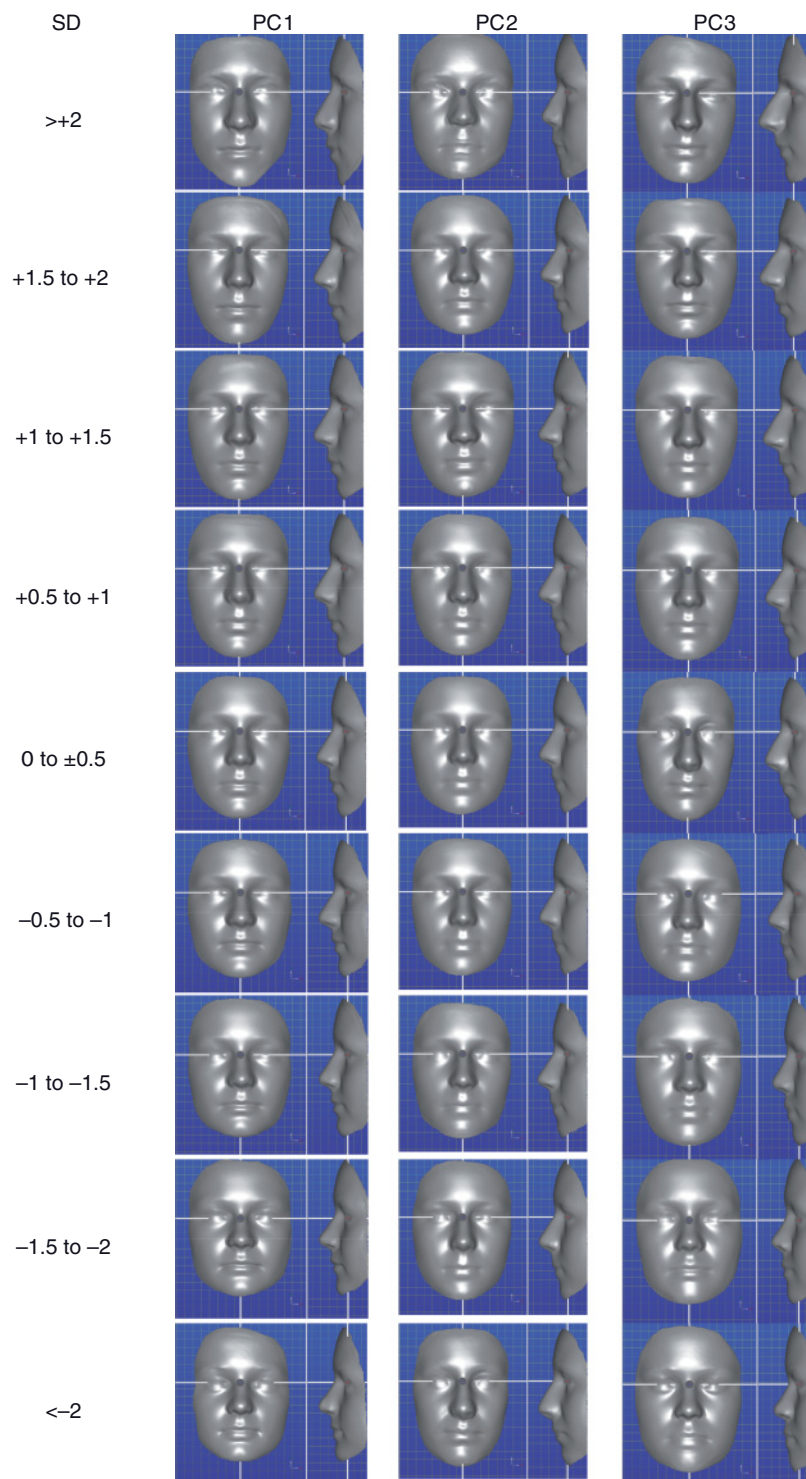


Figure 13.7 The facial variation ordered in 0.5 standard deviation increments ($\pm 2SD$) for the first three principal components: PC 1, face height; PC 2, intereye distance; PC 3, prominence of the nose. (Geomagic Quality; Geomagic, Inc., Research Triangle Park, NC, USA.)

89 mm, with an average of 73 mm. However, clinicians are more familiar with individual facial landmarks. The distance from the nasion (2) to the pogonion (21) ranged from 90.7 mm to 129.5 mm, with a mean of 106.5 mm, signifying a total difference in face height of 38.8 mm comparing the smallest with the largest face. Male faces on average are 2.6 mm longer than female faces.

With regard to the second principal component, the main effect is the distance between the eyes. The distance between the left and right centroids ranged from 53.3 mm (-2 SD) to 72.4 mm ($+2$ SD), with an average of 62.1 mm. The distance between the inner canthi ranged from 26.2 mm to 41.6 mm, with an average of 33.4 mm. The inner intercanthal distance tends to be on average 1.1 mm larger in males than females.

The third principal component is focused on the prominence of the nose. The prominence of the nose centroid ranges from 7.9 mm (-2 SD) to 16 mm ($+2$ SD). The prominence of the pronasale was on average slightly less in females (24.8 mm) compared with males (26.9 mm). The third component highlights the complexity in assessing shapes using a single landmark compared with the centroid, the latter taking into account more than one landmark and consequently providing significantly more information.

VISUALIZING FACIAL GROWTH

Accepting significant facial variation, it is reasonable to expect that individuals categorized according to facial size and shape will grow differently. Previous radiographic studies have suggested forward, vertical, and backward growth patterns.^{21,22,23}

Ninety-eight children near Cardiff, UK, have been followed from the age of 12 years old to 17 years old as part of the Cardiff 3D facial growth study.²⁴ 3D facial images were captured using Konica Minolta 900/910 laser cameras (Konica Minolta Sensing, Inc, Osaka, Japan), and images of the children were taken at 12, 12.5, 13, 13.5, 14, 15, and 16 years of age. Fifty individuals attended all follow-ups over the course of the study up to the age of 16 years of age, and nine children attended the 17-year-old follow-up. The quality and validity of the registrations can only be fully appreciated by sequentially placing the image in a short movie sequence, but the sequential images have been presented here. The various growth patterns can be examined closely, and the different increments of growth can be detailed.

In general individuals were reliable in repeating their NHP; however, head position alone is insufficient to register two facial shells taken on different occasions.¹² To follow the children's growth, each sequential facial shell was aligned to the inner canthi of the first facial scan taken in NHP at the age of 12 years of age to ensure vertical and lateral alignment with respect to the sagittal and transverse planes described in Chapter 7. In-house subroutines have been developed to align the surfaces to illustrate change. All images are aligned to a reference framework with a common origin (mid-inner-canthal point) indicated by the white axis indicator. All images are overlaid on a 10 mm grid to indicate relative changes.

Three examples of facial growth are highlighted, representing different facial sizes and shapes. As would be expected when taking facial images over intervals of 6 months or more, the face is subject to change as a result of facial growth and change in posture. The mandible may also be subject to movement and the facial soft tissues subject to a variety of facial expressions. The principal components were classified at 12 years of age.

Example 1

The growth of the face is seen in Figure 13.8 for an individual categorized by PC 1 $+0.5$ to $+1$ SD, PC 2 -0.5 to -1 SD, and PC 3 $+0.5$ to $+1$ SD. The significance of these classifications indicates a slightly long

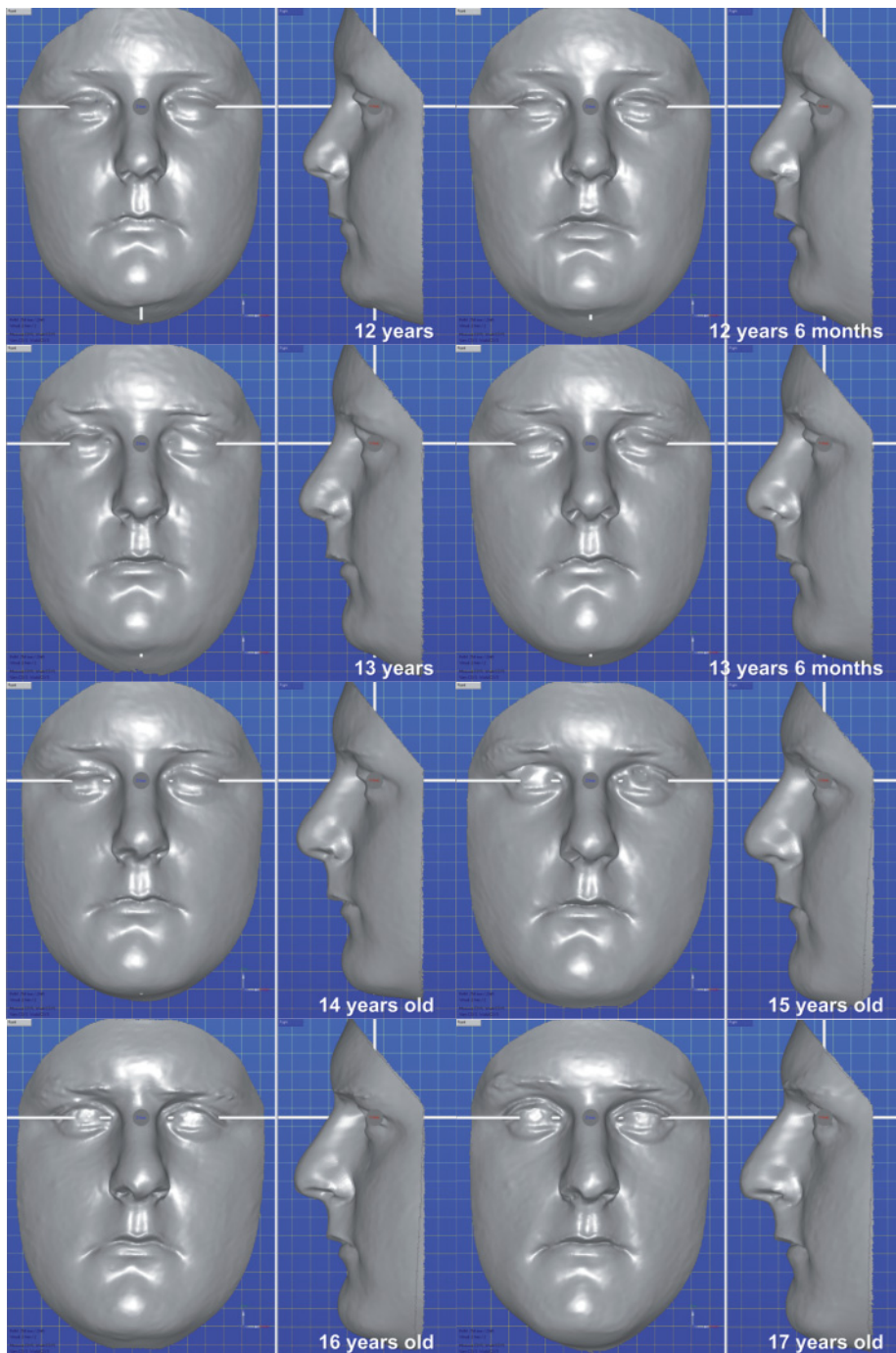


Figure 13.8 Male facial shells from the age of 12 to 17 years old (at the ages described in the text) registered on a common origin and three-dimensional framework. Classified according to PC 1 +0.5 to +1 SD, PC 2 -0.5 to -1 SD, and PC 3 +0.5 to +1 SD. (Geomagic Qualify; Geomagic, Inc., Research Triangle Park, NC, USA.)

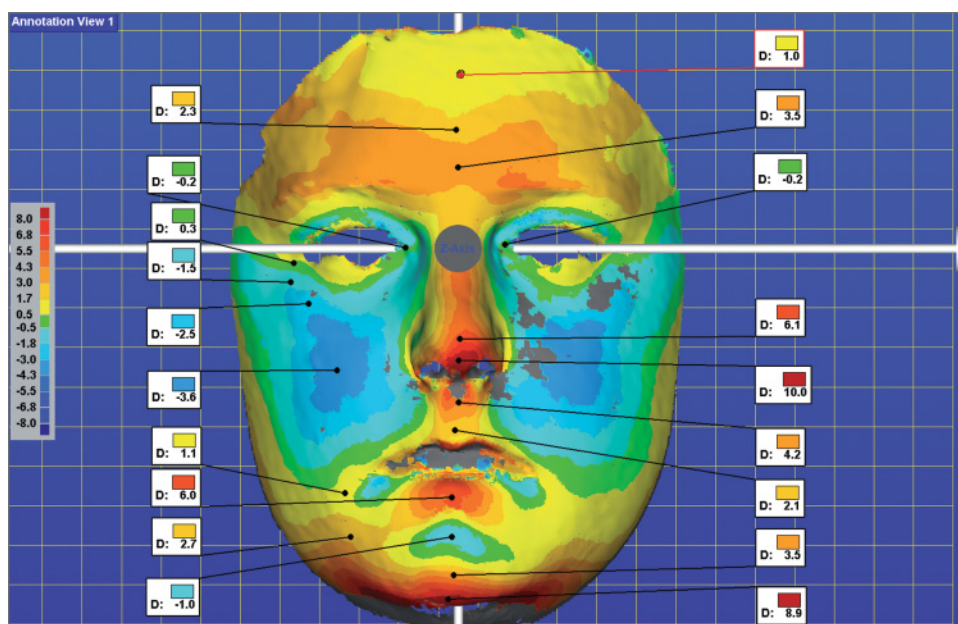


Figure 13.9 The color deviation map highlights the surface differences in facial shells at the age of 12 and 17 years old. (Geomagic Qualify; Geomagic, Inc., Research Triangle Park, NC, USA.)

face with the eyes slightly closer together and a slightly larger than average nose. The sequence shows subtle differences in facial expressions, particularly squinting at the age of 16 years. The facial morphology is retained throughout, with significant additions to overall face height highlighted at the inferior border of the mandible and a greater prominence of the nose and supraorbital ridges. Surface reduction is seen bilaterally with a loss of facial prominence in the infraorbital cheek area.

The magnitude of the changes is highlighted (Figure 13.9). The superimposition of the inner canthi indicates an error of less than 0.5mm. Inferiorly, the face height has increased by almost 9mm from a combination of the face growing downward and an increased height of the mandible. The nose has grown significantly forward and downward by 10mm, with the supraorbital ridges becoming more prominent by 3.5mm. The fullness of the cheeks has been reduced by 3.6mm.

Example 2

The growth of the face is seen in Figure 13.10 for an individual categorized by PC 1 +0.5 to +1 SD, PC 2 +0.5 to +1 SD, and PC 3 -0.5 to -1 SD. This information describes a slightly increased face height and inner canthal distance with reduced nose prominence. The sequence of surface facial shells highlights the gradual reduction of facial fat to a much more leaner and longer face with a greater length of the nose and an increase in total face height mainly contributing from the face growing downward and forward. The changes to the facial profile are highlighted in Figure 13.11, with detailed changes shown in Figure 13.12.

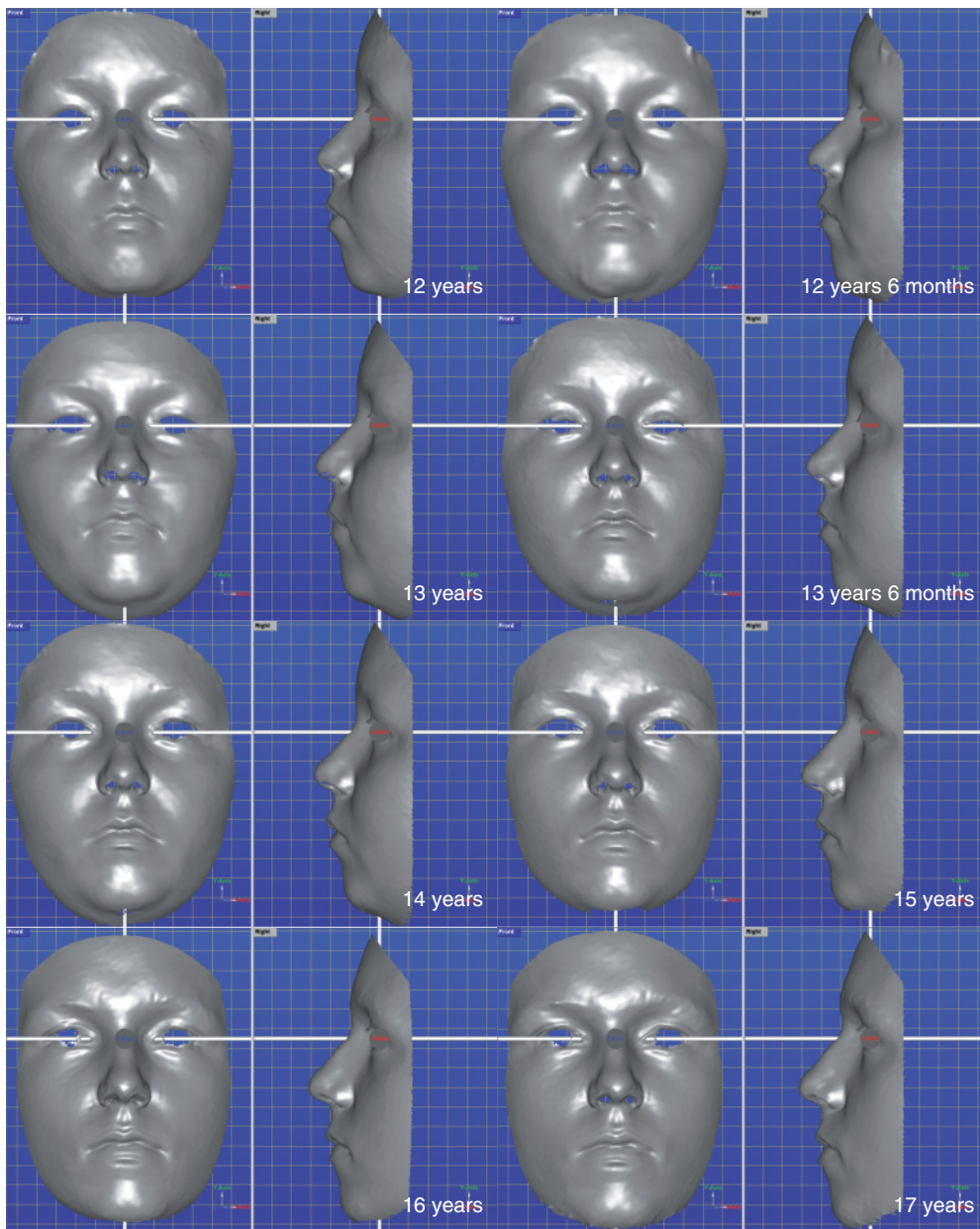


Figure 13.10 Facial shells from the age of 12 to 17 years (at the ages described in the text) registered on a common origin and three-dimensional framework. Classified according to PC 1 +0.5 to +1 SD, PC 2 +0.5 to +1 SD, and PC 3 -0.5 to -1 SD. (Geomagic Qualify; Geomagic, Inc., Research Triangle Park, NC, USA.)

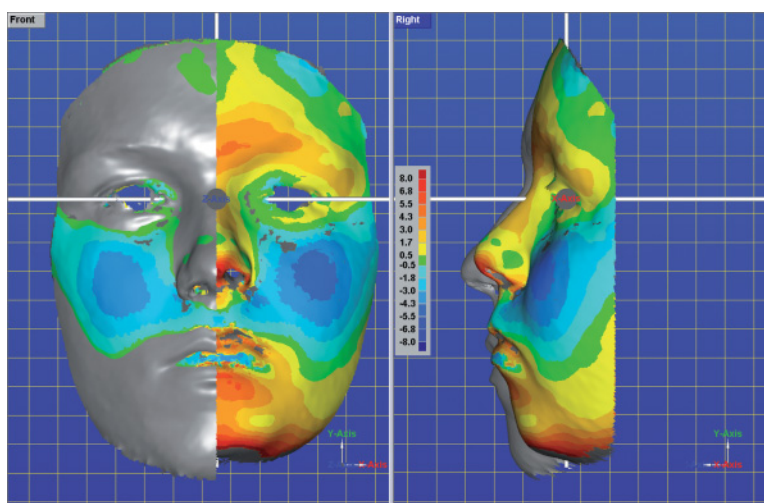


Figure 13.11 The color map indicates the shell-shell deviations between the 12- and 17-year-old faces. The 12-year-old shell is also superimposed on the 17-year-old shell (gray) to illustrate the sagittal change. (Geomagic Qualify; Geomagic, Inc., Research Triangle Park, NC, USA.)

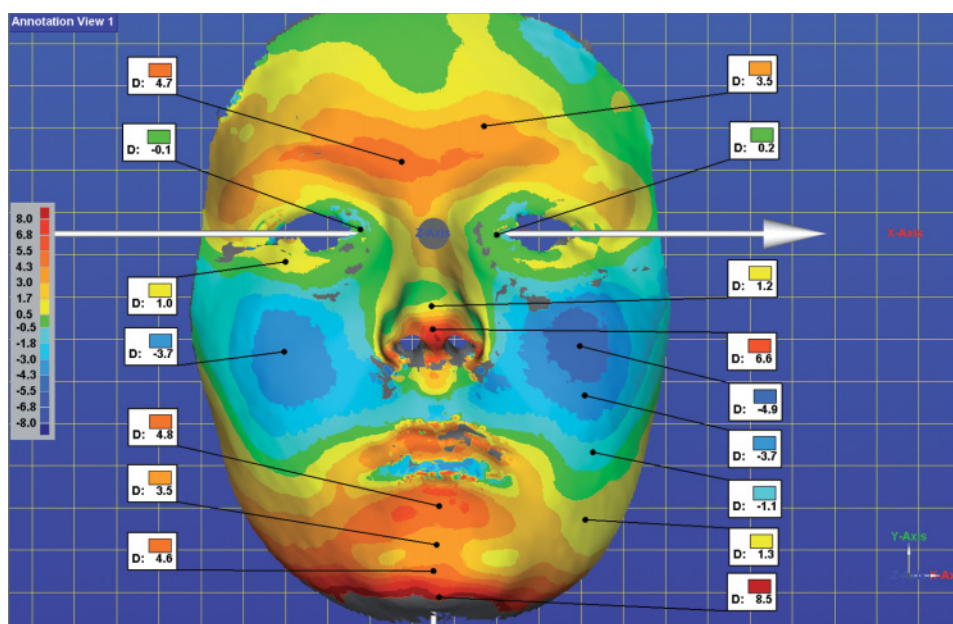


Figure 13.12 The color deviation map highlights the surface differences in facial shells at the age of 12 and 17 years old. (Geomagic Qualify; Geomagic, Inc., Research Triangle Park, NC, USA.)

Table 13.1 Directional vectors for the 21 facial landmarks

	Difference x	Difference y	Difference z	Distance
1 Glabella	1.1	-0.4	0.6	1.3
2 Nasion	-1.6	1.9	2.0	3.2
3 Endocanthion (L)	0.3	-0.7	-0.5	0.9
4 Endocanthion (R)	-0.7	0.1	-0.9	1.2
5 Exocanthion (L)	0.7	0.5	0.0	0.8
6 Exocanthion (R)	-3.5	-1.8	-2.6	4.7
7 Palpebrale superius (L)	-1.2	2.1	-0.6	2.5
8 Palpebrale superius (R)	-1.2	0.6	-0.7	1.5
9 Palpebrale inferius (L)	0.6	0.7	0.5	1.1
10 Palpebrale inferius (R)	-3.3	2.6	-2.1	4.7
11 Pronasale	-0.1	-1.9	5.0	5.3
12 Subnasale	-1.0	-3.2	2.6	4.2
13 Alare (L)	0.9	-2.3	3.5	4.3
14 Alare (R)	-2.1	-1.6	0.2	2.7
15 Labiale superius	-1.0	-3.3	1.5	3.8
16 Labiale inferius	-1.0	-3.9	0.8	4.1
17 Crista philtri (L)	-0.7	-5.8	2.3	6.3
18 Crista philtri (R)	-1.2	-4.3	2.3	5.0
19 Cheilion (L)	1.5	-3.8	0.2	4.0
20 Cheilion (R)	-1.9	-3.8	-0.7	4.3
21 Pogonion	0.3	-8.5	4.2	9.5

The superimposition error in the region of the inner canthi is less than 0.5 mm. The detailed changes indicate an increased face height (8.5 mm), increased length of nose (6.6 mm), and reduced prominence of the infraorbital and cheek regions (up to 5 mm). As the facial shells are aligned to a reference framework, the facial landmarks can be tracked with respect to the three planes of space and overall distance. The directional vectors for the landmarks of the face (differences between 12 and 17 years old) are shown for this individual (Table 13.1). The greatest change is the increase in face height (pogonion, 8.5 mm) with a lesser inferior movement of landmarks associated with the mouth. The nose (pronasale) is prominent by 5 mm. The inner canthal distance has increased by 1 mm. Taking into account the average changes in the three planes of space, the change in the *y*-axis is generally double that occurring in both the *x*- and *z*-axes.

Example 3

Backward growth is graphically illustrated in Figure 13.13. The individual can be classified as PC 1 +1.5 to +2 SD, PC 2 -1 to -1.5 SD, and PC 3 +1 to +1.5 SD, indicating a significant greater face height, a slightly increased inner canthal distance, and a reduced nose prominence. Essentially, the upper part of the face for this young lady does not change over the 4 years. However, the lower part of her face grows significantly downward between 12 and 13 years old, and there is significant modification in mandibular growth downwards and backwards from 13.5 to 16 years of age, highlighted by the mandible lying behind the white vertical origin indicator. There are minor facial movements during the 4 year period

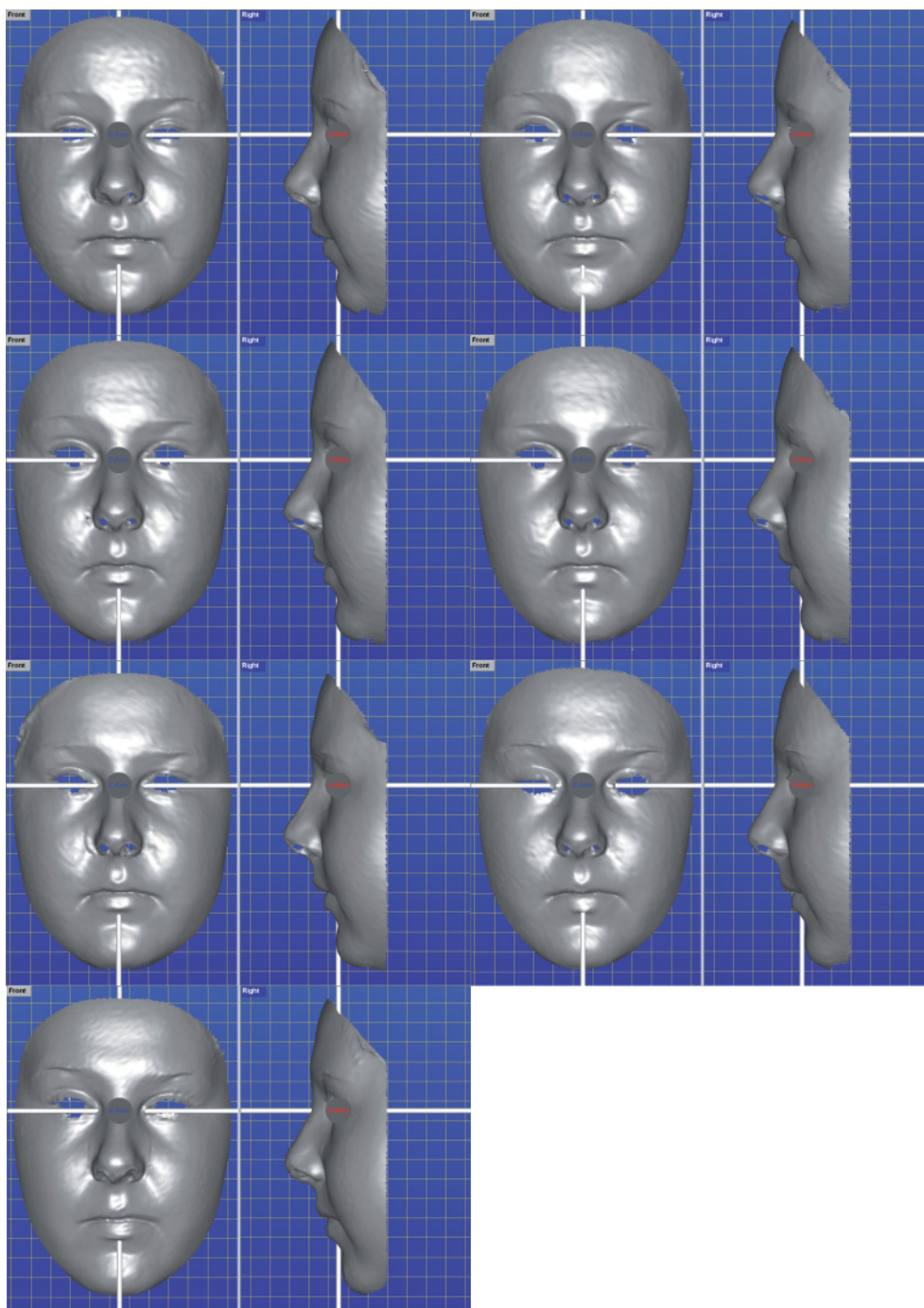


Figure 13.13 The facial shells are shown to illustrate facial changes from the age of 12 to 17 years (at the ages described in the text) registered on a common origin and three-dimensional framework. Classified according to PC1 +1.5 to +2 SD, PC 2 -1 to -1.5 SD and PC 3 +1 to +1.5 SD. (Geomagic Quality; Geomagic, Inc., Research Triangle Park, NC, USA.)

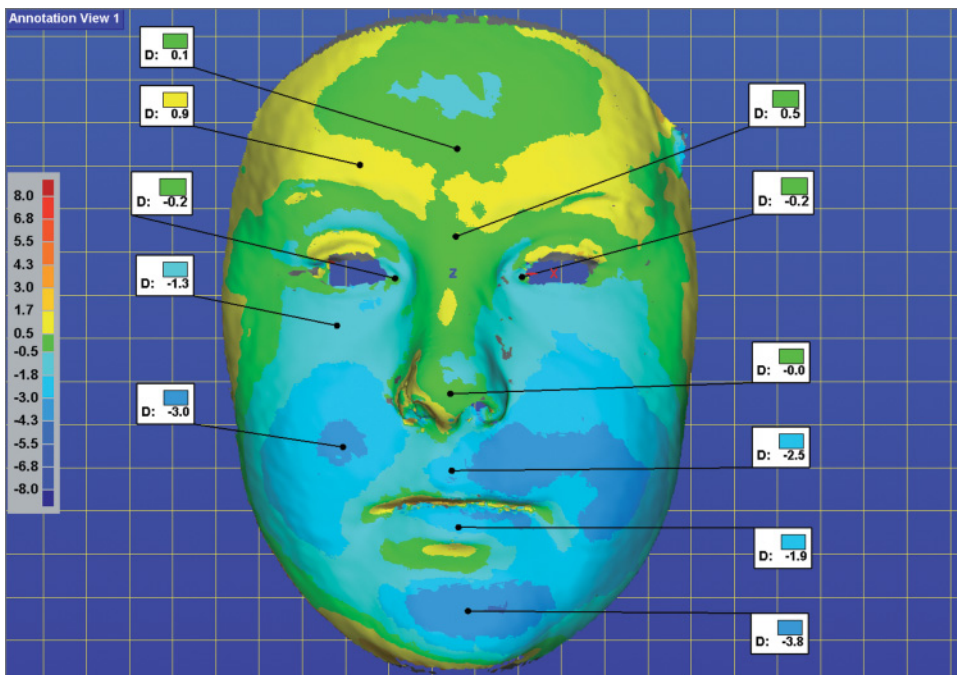


Figure 13.14 The color deviation map highlights the surface differences in facial shells at the age of 12 and 16 years of age. (Geomagic Qualify; Geomagic, Inc., Research Triangle Park, NC, USA.)

with blinking, raised eyebrows, and slight opening and closing of the mouth. Nevertheless, this movement does not detract from the overall changes in growth.

The detailed changes are illustrated in Figure 13.14. The changes in the face are much less than those illustrated for both boys. The superimposition on the inner canthi shows an error of less than 0.5 mm. There is a slight increase in prominence in the supraorbital region, but this is only about 1 mm. The lower part of the face indicates a downward and backward movement of about 3.8 mm in the chin region. There is very little difference in the size and shape of the nose.

Average facial growth 12 to 16 years of age

If the facial shells are averaged for the 27 boys and 23 girls at the ages of 12 and 16 years, it is possible to identify the gender differences in facial development.

Growth of the face – females

The facial changes in girls indicate a general widening of the face (about 2 mm) associated with an overall increase in face height of on average 3.4 mm and increase in size of the nose (approximately 1 mm; Figure 13.15). The majority of the face shows very little difference (± 0.5 mm).

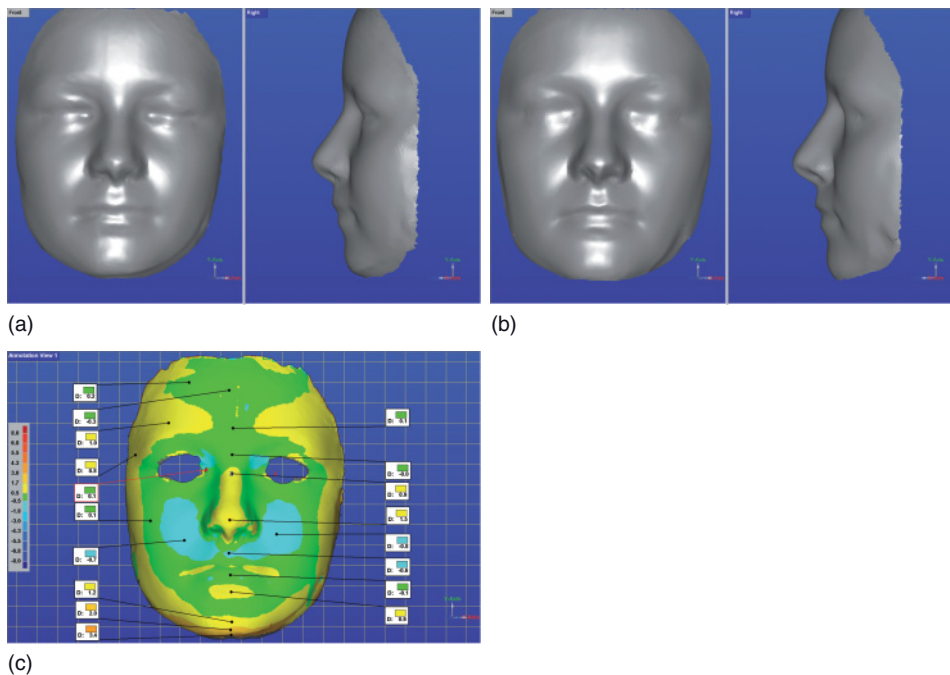


Figure 13.15 The average female facial shells for the 12-year-olds (a) and 16-year-olds (b), and detail of the differences when the two shells are superimposed (c). (Geomagic Qualify; Geomagic, Inc., Research Triangle Park, NC, USA.)

Growth of the face – males

Comparing the male facial shells between the ages of 12 and 16 years, there is a widening of the face and prominence of the supraorbital ridges by over 1mm, with a significant increase in face height (8mm), nose length (6mm), and bridge of the nose (2.5mm). Commonly, the temple regions become prominent (2.2mm). There is less prominence in the infraorbital and cheek regions, in the order of 1.5mm. The superimposition indicates a reduced prominence at the top of the forehead, which may result from a combination of surface remodeling and lack of surface data at the age of 12 years (Figure 13.16).

Male and female comparisons

It is common in boys to exhibit a short, round face at the age of 12 years of age and, as the child matures, for the buccal fat in the face to be reduced, consequently leaving a longer, leaner face. The general vertical direction of growth is highlighted (Figure 13.17). At the age of 12, the male faces tend to be longer in overall face height (3.4mm) and wider (1mm), with the nose showing greater prominence (1.5mm). However, the girls tend to have more prominent cheeks (<1mm).

The prominence of the cheeks prevails in the 16-year-olds and increases (1.9mm). There are significant differences in face height (8mm), nose (5mm), face width (2mm), and supraorbital ridges (1mm), with the males showing the greater size. The male features tend to be larger in all dimensions and also well defined and less rounded compared with those of females.

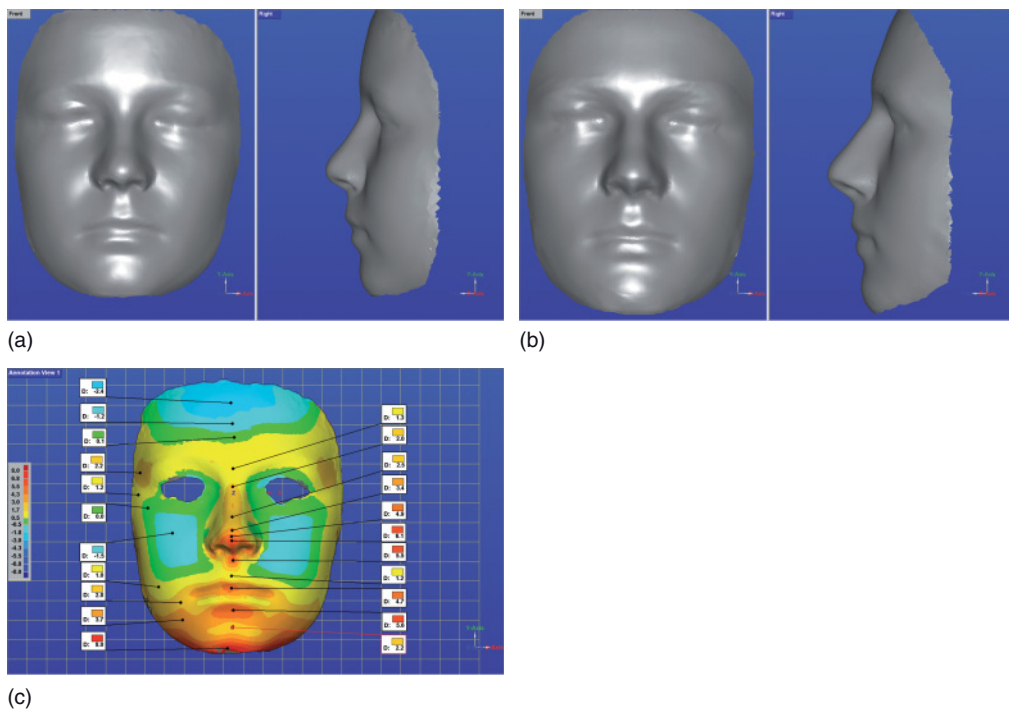


Figure 13.16 The average male facial shells for the 12-year-olds (a) and 16-year-olds (b), and detail of the differences when the two shells are superimposed (c). (Geomagic Qualify; Geomagic, Inc., Research Triangle Park, NC, USA.)

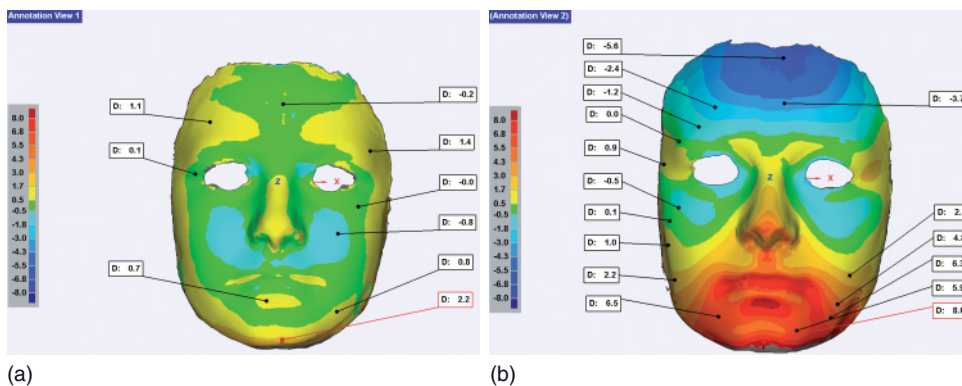


Figure 13.17 The average female and male shells compared at age 12 years (a) and 16 years (b). At 12 years, the males tend to have larger faces in width and height. At 16 years, the face height is significantly longer in males compared with that of females, with increased prominence of the supraorbital ridges and nose and mouth region. At both ages, the female cheeks tend to be prominent compared with boys (approximately 1 mm). (Geomagic Qualify; Geomagic, Inc., Research Triangle Park, NC, USA.)

CONCLUSION

The use of surface scanning provides a unique opportunity to noninvasively capture the face in three dimensions. Ideally, the face should be scanned every 6 months to evaluate changes. The detailed changes are accurate to ± 0.5 mm. Currently, evaluations are still in the research domain as the tools to align, register and evaluate images have not yet reached full commercialization. However, the authors are certain that surface scanning techniques will become an integral part of evaluating diagnosis, treatment planning, and treatment outcomes in the coming decade.

Please refer to the supporting companion website at: www.wiley.com/go/kau

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Use of Digital Models/Dental Casts and their Role in Orthodontics/Maxillofacial Surgery

Kelvin W.C. Foong

INTRODUCTION

The dental plaster model is the physical three-dimensional (3D) representation of the dentition and oral anatomy that clinicians can hold in their hands and use to view the dental occlusion in any 3D spatial perspective. It is a necessary clinical and legal¹ record for diagnostic purposes and the planning of treatment in orthodontics, prosthodontics, oromaxillofacial surgery, and cleft lip and palate surgery, where dental interceptive intervention is indicated. In addition to its role as a record for diagnosis and treatment planning, the dental plaster model is routinely used as the positive and accurate proxy for the fabrication of oral appliances and prostheses in the definitive treatment process. With the physical dental model, clinicians have been able to:

- perform measurements of intra-arch tooth size and inter-arch parameters (the overjet) using calipers;
- rearrange the positions of the teeth to simulate the prospective dental arch alignment and occlusion, as in the case of orthodontic planning (the Kesling setup²);
- simulate the expected positions of the dental arches for occlusal wafer construction immediately prior to orthognathic surgery.

From the physical measurements of the mesiodistal widths of the teeth, the Bolton analysis³ and the estimation of the degree of crowding or spacing are determined. In the Kesling setup, the physical rearrangement of the dental arch form to determine whether arch space may be gained through an extraction of teeth requires a drill-and-saw method to section parts of the plaster model and reset the plaster crowns of the teeth in a new arch arrangement. It is a time-consuming procedure and much disliked by clinicians.



Figure 14.1 (a) The Minolta VIVID 900 surface laser scanner (Konica Minolta Sensing, Inc, Osaka, Japan) and (b) the NextEngine (Santa Monica, CA, USA) 3D scanner.

With the advancement of computer technology in the area of image acquisition, the accuracy and speed with which a physical object may be converted from a physical to a 3D digital form has improved significantly over the last 10 years. The cost of a surface laser scanner to accurately acquire the surface topology of a physical object is also no longer prohibitive. Compared with a portable industrial surface laser scanner from Konica Minolta Sensing, Inc (Osaka, Japan), the VIVID 900 model, which was priced at about US\$40,000 some 5 years ago, a 3D desk-top surface laser scanner from NextEngine, Inc (Santa Monica, CA, USA) can at the time of writing be bought for under US\$3,000 (Figure 14.1).

Such technologic improvements and cost reductions permit the application and adoption of modern image acquisition technology to dentistry. This has huge potential specifically in rendering the current processes in orthodontic diagnosis, the planning of treatment, and simulations more efficient and substantially more effective. Hence, 3D digital dental models could offer distinct technologic and clinical application advantages over physical plaster models.

TECHNOLOGIC ADVANTAGES OF DIGITAL DENTAL MODELS

There are several technologic advantages, described below. First, digital dental models, in that they are computer images by nature, are “unbreakable” and not subject to physical wear. In addition, they require no laboratory setup to duplicate them as the images can be replicated easily and quickly.

The storage of multiple sets of digital dental models requires little physical space and cost. They can be contained within the size of a conventional thumb-drive, and therefore free up valuable physical storage space that could be used for more productive purposes. The price of computer memory storage



Figure 14.2 The accurate rapid-prototyped model (right) of the original dental model (left), which was created from computed tomographic scanning of the original dental model.

has never been lower; the retail price in April 2009 of a 4 gigabyte thumb-drive was approximately US\$10. Since each digital dental model (via surface laser scanning) takes up between 5 and 10 megabytes of computer memory space, one could technically store 400–800 laser-scanned digital dental models in a 4 gigabyte thumb drive.

Accessibility to and security of an archive of digital dental models can be easily provided around the clock. The retrieval of digital data is quick through a dedicated computer server, and permissibility to view the digital dental models may be granted via secure passwords. Hence, it is impossible to “misplace” digital dental models or lose them through “theft.”

Additionally, as a form of digital data, they can be sent via high-speed broadband networks from one geographic location to another across miles in a blink of the eye in compressed and uncompressed modes. Using commercially available digital document technology through the software Adobe Acrobat 9 Pro Extended (Adobe Systems, Inc, San Jose, CA, USA), the 3D image of the digital dental model can be easily “inserted” as an image file into a portable document format (.pdf) text file, and sent to a recipient via email; the recipient can then view and interact with the 3D image of the dental model through Adobe Reader version 7.07 and higher (Adobe Systems, Inc). This technology renders visual communication and collaborative treatment between interested parties a reality at a high level of information clarity and efficiency without expensive freight charges.

Rapid prototyping reproduction from digital to physical forms can be achieved when needed. In the event of needing to convert a digital dental model into a physical hard copy, the digital image of the dental model can be easily converted to an appropriate format suitable for the rapid prototyping system to print out the 3D physical shape of the dental model (Figure 14.2).⁴

CLINICAL APPLICATIONS OF DIGITAL DENTAL MODELS IN ORTHODONTICS AND MAXILLOFACIAL SURGERY

Quantitative measurement of dental and oral anatomy

On acquiring the 3D image of the plaster dental model from contemporary 3D scanners, the digital image undergoes a series of “processing” steps before the scanned images can be made meaningful and useful to the clinician.

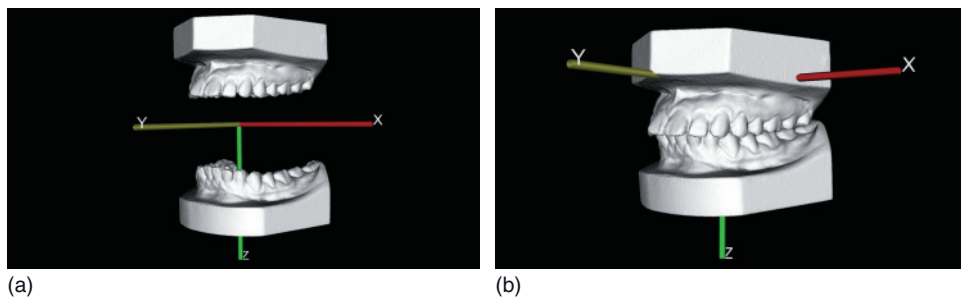


Figure 14.3 (a) The individually scanned digital maxillary and mandibular models, and (b) with the models in occlusion, in natural “white” color and texture.

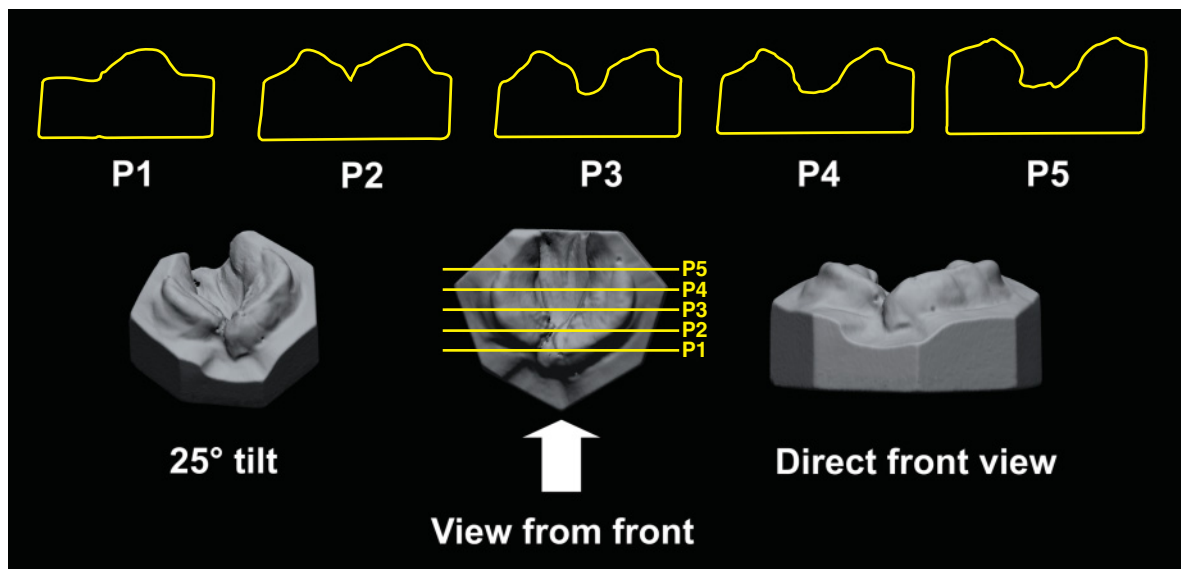


Figure 14.4 Digital model of a cleft palate that is sliced in the anteroposterior direction from planes P1 to P5. The corresponding palatal contour is viewed further above from P1 to P5.

The surface of the digital dental model is mathematically represented as a surface of points (vertices) joined together to form a network lattice of triangles. The overall surface color and texture is displayed when each triangle is computer-coded for that specific color (a color map) and texture (a texture map). Color and texture added to the surface of the image provide a realistic visual representation of the plaster dental model (Figure 14.3).

With accompanying programming for capability to make geometric measurements within a graphical user interface environment, any linear, angular, area, and volumetric measurements, or a combination of these measurements, can be taken from the surface on the 3D image of the digital dental model.

Digital models can be “sliced” in any preferred orientation plane to reveal the surface contours (Figure 14.4) of the dental and oral anatomy⁵ and the spatial relationship of the contours of teeth surfaces in an

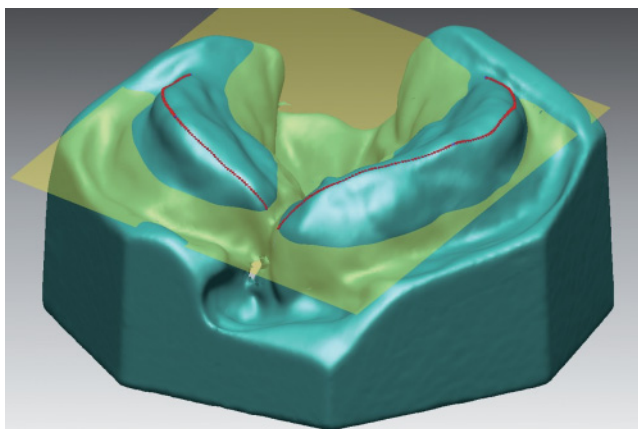


Figure 14.5 The boundaries of the volume of the cleft palate defect defined digitally by the white-colored base plane and the ridges of the palatal segments.



Figure 14.6 (Top) The “segmented” frontal and side views of the occlusion. (Bottom) The entire occlusion from the lingual perspective.

occlusion. From the “slices,” the digital anatomic contours can be highlighted. Linear and area measurements can be made from these two-dimensional (2D) slices. Volume measurements (Figure 14.5) can also be made from the digital anatomy based on the slice plane orientation⁵ and predefined anatomic reference indicators.

Visual analysis of the occlusion

Digital models, with the aid of computer graphics, permit the close-up viewing (right in front of your eyes) of the occlusion from the posterior end (Figure 14.6), which is not possible when doing a clinical evaluation of the occlusion. Although physical plaster models permit the user to view the lingual occlusion from the back, the field of view is significantly limited by the left and right teeth structures. The occlusal contacts and the spatial relationships of cusps to cusps and cusp to occlusal fossa can be better visualized in this manner.⁶

Visualization of mandibular movement during mastication

With the added dataset of jaw movement tracings of chewing cycles from jaw kinematic appliances, the dynamic relationship of the digital maxillary and mandibular dental arches can be created to reveal the chewing cycle in 3D space. If the individual's cone beam computed tomography (CBCT) data for the maxilla and mandible are available, the digital dentition can be superimposed accurately over the CBCT dentition. The mandibular jaw movement cycle in 3D space can be represented visually.⁷ Digital tracking and tracings of the movement of the lateral poles of the mandibular condyles and of the lower midline incisor positions can be displayed to indicate the anatomic positions of these landmarks during the chewing cycle.

Treatment planning through nondestructive digital "movement" of teeth

Before digital tooth movement can be performed on the computer, the 3D digital image must be subjected to the process of image segmentation.⁸ As the entire surface of the digital dental model is represented by the network lattice of vertices and triangles, the surfaces representing the tooth crowns will have to be separated (Figure 14.7) from the surfaces representing the gingiva and mucosa via this computer process. This process may be completely automated, semi-automated, or completely manual, whereby the anatomic line representing the gingival margin is established digitally and the crown surface is delineated from the digital gingiva and mucosa. After image segmentation in which the digital crowns are "freed" to be moved, digital tooth movement can take place.⁹

After segmentation, each individual digital tooth can be moved on screen in any preferred direction and into a new position to represent "tooth movement," or the digital crown can be eliminated to simulate an "extraction." This capability permits the user to test out different options of nonextraction/arch expansion treatment and extraction treatment (Figure 14.8) and visualize the dental arch forms and simulated occlusions of the various options before definitive treatment.

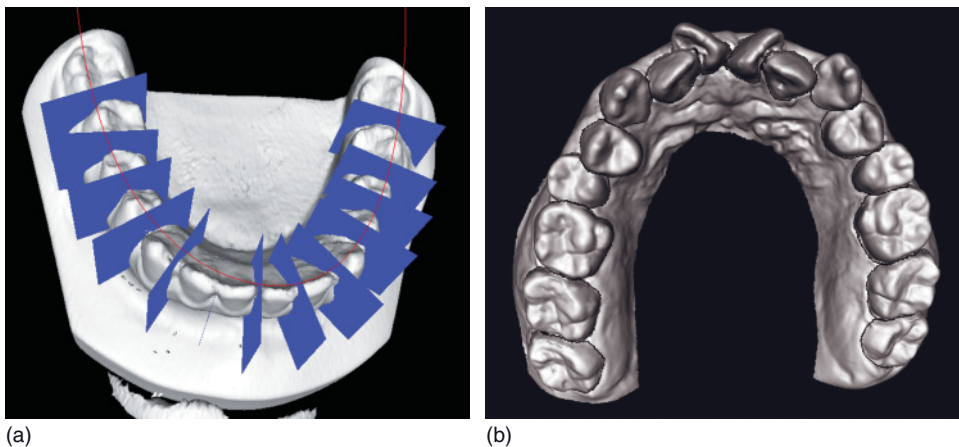


Figure 14.7 The process of image segmentation in which (a) the tooth crowns are separated from one another at the interdental area by the blue-colored planes. (b) Each tooth crown is separated from the digital gingiva and mucosa as evidenced by a dark line at the digital gingival margin.



Figure 14.8 Based on the original pre-treatment arch form from Figure 14.7b, this figure shows (left) the nonextraction/arch expansion approach and (right) the extraction of two upper first premolars and the effect on the dental arch form.

The actual treated occlusion and dental arch forms can be digitized and compared with the preferred digitally simulated occlusal outcome to assess the degree of parity between the simulated and actual outcomes. A comparison of the positional characteristics of each tooth at simulation and at the final treated position can be made to determine parity between the simulated and actual clinical outcome. When the entire comparative process is performed on a serial basis, it becomes a valuable educational tool for training orthodontic residents in treatment planning.

Evaluation of changes to the dentition arising from treatment

It is possible, with the superimposition of two or more digital dental models, to evaluate in 3D space the intra-arch and inter-arch changes arising from orthodontics, jaw surgery, and growth modification procedures. The intra-arch and inter-arch tooth position changes (primarily the central incisor and first molar positions) arising from orthodontic, growth modification, and orthognathic surgery have traditionally been visualized through 2D comparative tracings derived from the superimposition of pre- and post-treatment lateral cephalograms. Through the use of digital dental models, the spatial changes in three planes for each tooth within each dental arch can be visualized.

The method proposed uses the patient's digital lateral cephalogram as a reference template to orientate the maxillary dental arch digital model to the digital lateral cephalogram.^{9,10} Slicing each digital dental model along the midpalatal raphe in the sagittal plane reveals the contour of the palatal shelf, which is then matched in shape to the corresponding palatal contour outline on the digital lateral cephalogram (Figure 14.9).

The sagittal plane slice at the midpalatal raphe is created as a perpendicular to the triangular plane formed by three points on the maxillary occlusal plane represented by the mesiopalatal cusp tips of the first molars and the incisal embrasure point of the upper central incisors. The orientation of the digital maxillary model via this method results in the digital lateral cephalogram dividing the maxillary model at the midpalatal raphe, with the halves of the digital dental model on each side of the digital radiograph (Figure 14.10).

After orientating the digital maxillary dental arch, the digital mandibular dental arch is easily brought into anatomic maximal intercuspal occlusion with the maxillary arch. Accordingly, the intra-arch tooth position changes of the maxillary¹⁰ (Figure 14.11) and mandibular¹¹ dental arches can be visualized by

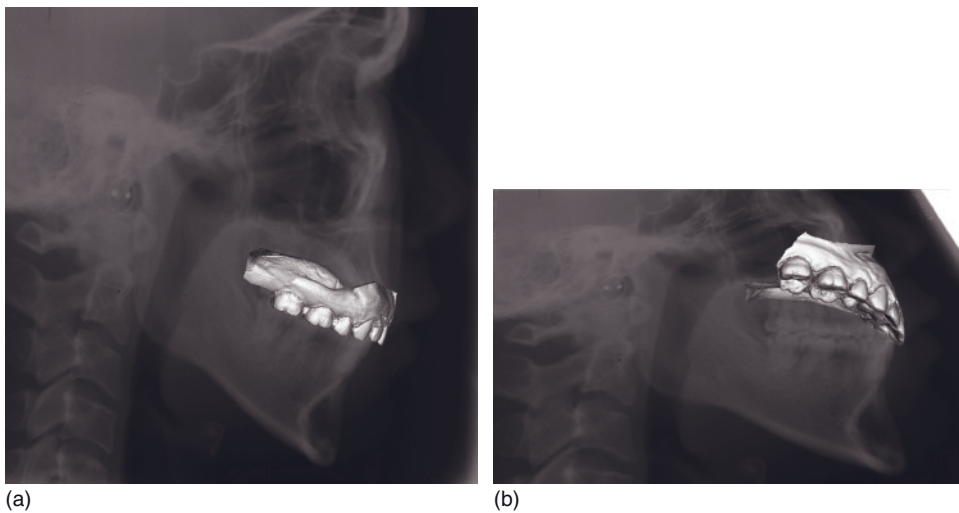


Figure 14.9 (a, b) Two views of the spatial orientation of the digital maxillary model to the digital lateral cephalogram.



Figure 14.10 The digital maxillary dental model divided in half by the digital lateral cephalogram.

using traditional regional superimposition reference lines and anatomic features for the maxillary dentoalveolar region (anterior nasal spine to posterior nasal spine fixed at the anterior nasal spine point) and mandibular dentoalveolar region (inner outline of the cortex of the mandibular symphysis) with the pre- and post-treatment digital lateral cephalograms.

With the digital models in occlusion, superimposition on the cranial base for inter-arch changes can be made via the reference line (sella to nasion fixed at the sella point). The validity of this method relying

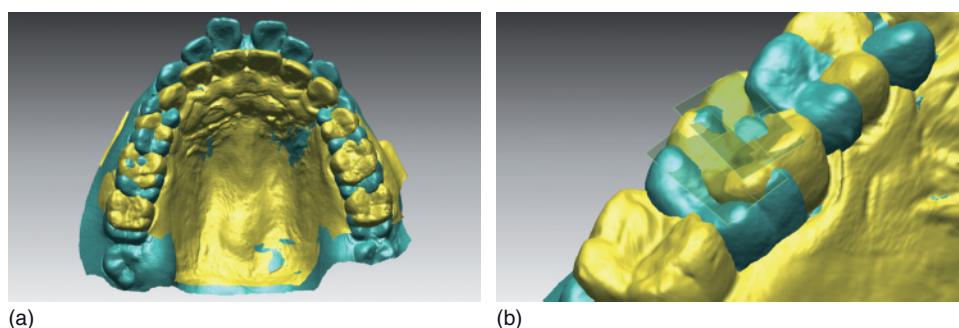


Figure 14.11 (a) The change in tooth positions from the darker-colored pre-treatment position to the lighter-colored post-treatment state. (b) Differences in crown inclination can also be determined by constructing reference frames over the occlusal surfaces of the teeth.

on the digital lateral cephalogram as a reference template hinges on the assumption that there is no obvious facial asymmetry and no occlusal plane cant, and that the deviation of the upper and lower dental midlines is less than 5 mm from the facial midline.

In the event that an accurate 3D facial image of the individual is available, the individual's digital 2D lateral cephalometric image may be aligned with the individual's 3D facial image via the mid-sagittal plane facial outline. The alignment of the digital dental models with the lateral cephalometric image will therefore relate the digital dentition to the individual's facial shape. With these two forms of spatial alignment, the reality of comparing 3D dentofacial changes arising from orthodontic treatment, jaw surgery, and growth modification is now possible with the superimposition of the pre- and post-treatment digital lateral cephalometric images at the cranial base reference line sella–nasion fixed at the sella point.

Review of treatment progress in the orthodontic preparation for orthognathic surgery

Assessment of additional occlusal and arch form changes needed as a progress indicator for orthodontic decompensation prior to orthognathic surgery is entirely possible with digital dental models. In the pre-surgical preparation period of orthodontic decompensation, there is a need, especially in Class III malocclusion cases where mandibular jaw setback and/or maxillary jaw advancement is indicated, to determine whether the amount of orthodontic tooth position change that has been achieved is adequate.

From the digital dental model of the pre-treatment dental arch, the expected digital dental arch at the end of the decompensation can be simulated. This is then compared with the digital dental model of the “progress” digital dental arch based on the method of registration mentioned above. Further tooth movement that is needed can be easily visualized for comparison with the simulated end-of-decompensation and “progress” digital dental models.

Fabrication of surgical splints for orthognathic surgery

In cases where a single- or double-jaw orthognathic procedure is indicated, the use of digital dental models has the potential to bypass the need for a laboratory setup to create the surgical splints to

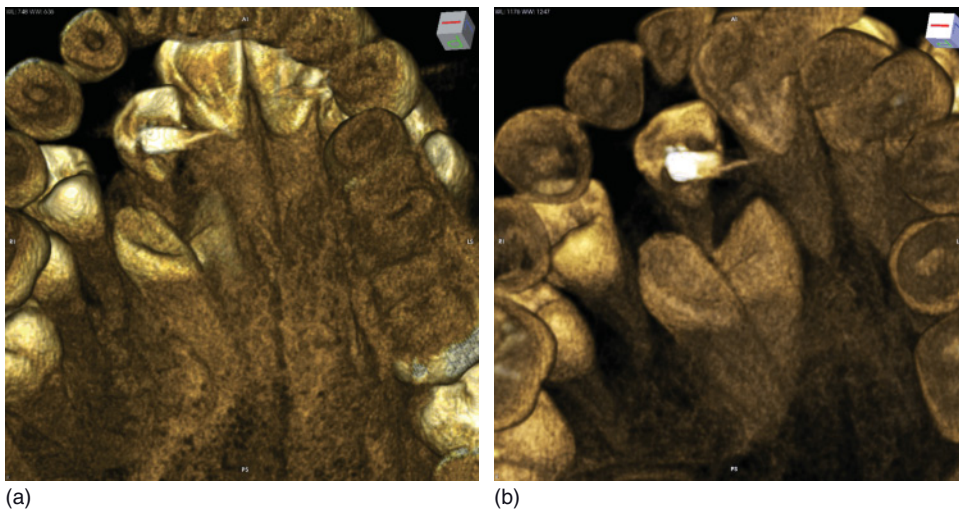


Figure 14.12 The external (a) and internal (b) anatomy of the anterior right segment of the maxillary bone, with two buried permanent teeth.

position the maxillary and mandibular dentition in the desired occlusion. After simulating the expected immediate post-surgical occlusion of the 3D digital models, an accurate digital model of a surgical splint may be created from the negative forms of the digital surfaces of the maxillary and mandibular dentitions. The digital model of the surgical splint will then be sent for rapid prototyping to print out one or more physical hard copies that will be used during the actual jaw surgery.

Complementing treatment decision-making with cone beam computed tomography images

The proliferation of CBCT scanners in clinical dental and oromaxillofacial surgical practices for diagnostic and planning purposes has given clinicians the ability to view the orofacial anatomy in the third dimension at a lower cost and radiation dose^{12,13} to patients. The displayed images reveal external and internal anatomy (Figure 14.12) through the alteration of the contrast function in the accompanying software. Internal anatomy is embedded in the image and is “fixed” in the anatomic location and relationship with other anatomic structures. While most conventional DICOM (Digital Imaging and Communications in Medicine) viewers permit the clinician to view the anatomic structures from any preferred orientation and magnification, these viewers do not have the capacity to permit the user to separate and isolate the embedded image of the internal structure, such as buried teeth in the maxilla, from the other structures.

Accurate and patient-specific computer models of the dentition are needed to define and represent the anatomy of the teeth distinctly from the bone and other anatomic structures in the CBCT image. The clear separation and definition of the teeth from the surrounding anatomy via computer image segmentation will enhance the user’s ability to “see” and, if needed, “move” the teeth. This significant

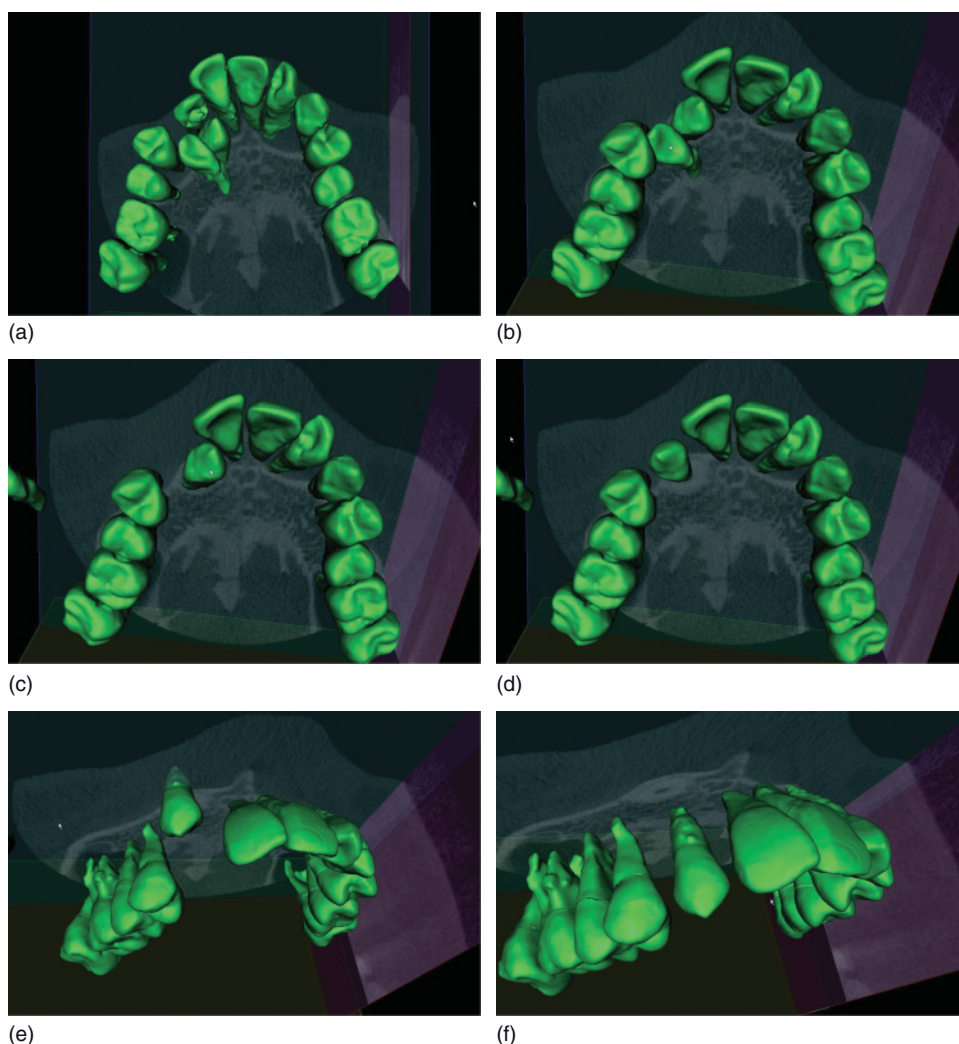


Figure 14.13 Resolving the spatial problem resulting from a buried and transposed maxillary right canine and lateral incisor. (a) Pre-treatment positions of the buried teeth. (b) The upper right primary lateral incisor is removed. An attempt to move the buried upper right lateral incisor buccally is “blocked” by the first premolar. (c) The buried upper right lateral incisor is “extracted” digitally. (d) The upper right canine is no longer blocked from rotational correction and is digitally rotated. (e) The right perspective view shows that the upper right canine is still in a superior position. (f) The upper right canine has been brought to the level of the occlusal plane.

advantage becomes apparent in cases where multiple teeth are buried and a decision has to be made on which teeth to remove (Figures 14.12 and 14.13). The digital models of the teeth shown in Figure 14.13 are created by applying a computer algorithm to “grow” the teeth in 3D shape from the 2D multiplanar orthogonal views derived from the CBCT data.¹⁴ Figure 14.13 shows in sequence from (a) to (f) how the spatial problem of a buried and transposed maxillary right canine and lateral incisor is resolved.

CONCLUSION

Digital dental models do offer a significant value proposition over plaster dental models. The technologic advantages have the potential to reduce operational cost and improve efficiency in communication. In the clinical environment, the digital dental models complement the diagnostic and treatment planning processes through digital simulations made singly on the dental models or on the combination of digital models with other forms of image modalities. Clinicians intending to work with digital dental models will need to learn to use the computer to understand the nature of and competently view 3D image data in order to derive maximal information for clinical decision-making.

ACKNOWLEDGMENTS

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15

A Custom-fitting Surgical Guide

*Richard Bibb, Dominic Eggbeer, Alan Bocca,
Peter Evans, and Adrian Sugar*

INTRODUCTION

Over the last decade, rapid prototyping (RP) techniques have been employed widely in maxillofacial surgery. This has tended to concentrate on the reproduction of exact physical replicas of patients' skeletal anatomy, which surgeons and prosthetists use to help plan reconstructive surgery and prosthetic rehabilitation.¹⁻¹⁰

Developments in this area are moving towards exploiting advanced design and fabrication technologies to design and produce implants, patterns, or templates that enable the fabrication of custom-fitting prostheses without requiring a model of the anatomy to be made.¹¹⁻¹⁵ However, there is also growing desire from clinicians to conduct more of the surgical planning using three-dimensional (3D) computer software. RP technologies provide a method of producing custom-fitting surgical guides to transfer the computer plan to the operating theater.

Previous work on the application of RP technologies in the manufacture of surgical guides has concentrated on the production of drilling guides for oral osseointegrated implants.¹⁶⁻¹⁸ This in turn led to commercially available dental implant planning software and stereolithography drilling guides (SimPlant, SurgiGuides; Materialise NV, Leuven, Belgium). There has also been limited research carried out in the use of surgical guides in facial prosthetic rehabilitation and orthopedic surgery.¹⁹⁻²⁴ This chapter will describe one case study in detail, involving the design, production, and implementation of a surgical guide.

RP surgical guides have to be accurate, robust, rigid, and able to withstand sterilization. Due to these requirements, the majority of surgical guides have been produced using stereolithography, which necessitates local reinforcement of the guides using titanium or stainless steel tubes, as well as low-temperature sterilization methods such as the use of ethylene oxide.

The recent availability of systems capable of directly producing fully dense solid parts in functional metals and alloys has provided an opportunity to develop surgical guides that exploit the advantages of RP while addressing the physical deficiencies of previous RP guides. Surgical guides produced directly in hard-wearing, corrosion-resistant metals require no local reinforcement, can be conveniently autoclaved along with other surgical instruments, and are much less likely to be inadvertently damaged during surgery. The use of much stiffer metal materials also enables surgical guides to be made much smaller and thinner while retaining sufficient rigidity. This benefits surgery as smaller incisions can then be made, and the surgeon's visibility and access are significantly improved.

PLANNING AND DESIGN

This section describes the approach taken to planning, designing, and producing the surgical guide reported in the following case study. A 3D computed tomography (CT) scan had already been acquired for diagnosis and planning of the patient's treatment, and these images were subsequently utilized for the planning of the surgery.

Step 1: 3D computed tomography scanning

The patient was scanned using 3D CT (1 mm slices with 0.5 mm overlap) to produce 3D computer models of the anatomic structures required. The CT data were exported in DICOM file format, which was then imported into medical data transfer software (Mimics; Materialise NV). This software was used to generate the highest possible quality .stl data files of the patient's soft tissue and skeletal anatomy. The .stl files were then imported into the computer-aided design (CAD) software.

Step 2: Computer-aided surgical planning and design of the surgical guide

The quality of the bone was assessed using Mimics software (Materialise NV). Tools in the software enable measurements to be taken and the density (Hounsfield number) over a given section line to be shown (Figure 15.1). This enables the precise depth and density of the bone to be measured in the region

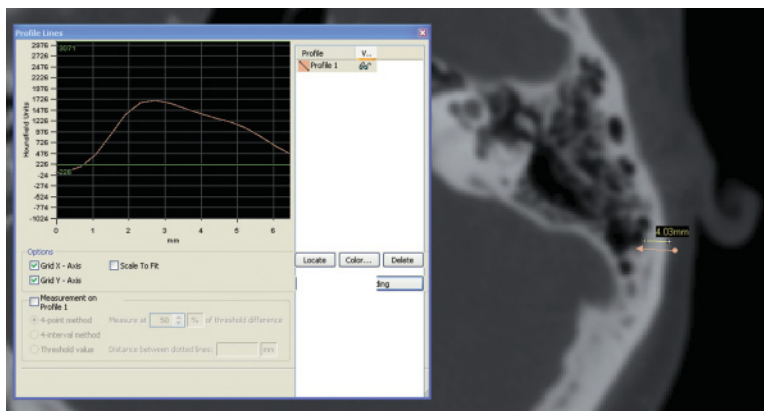


Figure 15.1 Bone depth and density being measured using Mimics software. (Image courtesy of Materialise®.)

of the intended implant sites. Other implant planning software packages have similar functions to assess bone quality at implant sites.

The CAD package used in this case study (FreeForm; SensAble Technologies, Inc, Woburn, MA, USA) was selected for its capability in designing the complex, arbitrary but well-defined shapes that are required when designing custom appliances and devices that must fit the human anatomy. The software has tools analogous to those used in physical sculpting and enables a manner of working that mimics that of the maxillofacial prosthetist working in the laboratory. The software utilizes a haptic interface (Phantom Desktop haptic interface; SensAble Technologies Inc) that incorporates positioning in 3D space and allows rotation and translation in all axes, transferring hand movements into the virtual environment. It also allows the operator to feel the object being worked on in the software. The combination of tools and force feedback sensations mimics working on a physical object and allows shapes to be designed and modified in an arbitrary manner. The design techniques utilized and their benefits have been previously recognized and reported.^{13,14,23,25}

First, the data on the patient's anatomic structures were imported into the CAD software. To plan the placement of implants for the retention of a prosthetic ear, the patient's unaffected ear was copied and laterally inverted (mirrored). The clinicians then positioned this ear relative to the head to provide the best possible esthetic reconstruction. This enabled the ideal position of the implants to be identified, directly in line with the antihelix. Two cylinders of the appropriate size were positioned to represent the implants (Figure 15.2). The third cylinder is for the implant to retain the bone-anchored hearing aid.

The soft tissue data were then removed from view so that the location of the implants on the bone could be evaluated. The bone was assessed to ensure adequate quality and thickness, and if necessary the implant locations were adjusted. A surgical guide was then designed to fit onto the bone surface surrounding the immediate area of the implants. The guide was designed to be 1 mm thick and to cover areas of anatomic shape that would assist positive location on the bone surface. The position of the implant cylinders was transferred to the guide design by Boolean subtraction to leave holes indicating

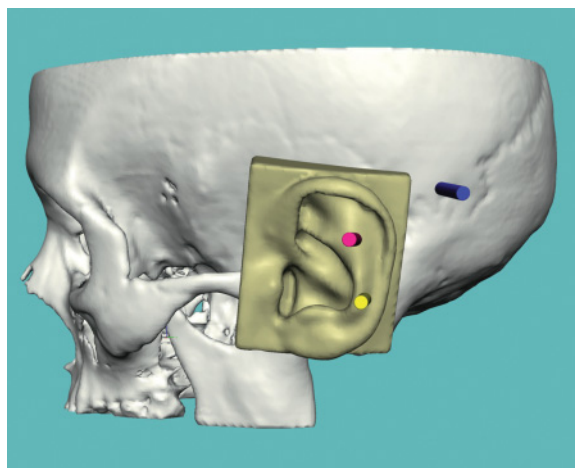


Figure 15.2 Laterally inverted ear and implant cylinders.

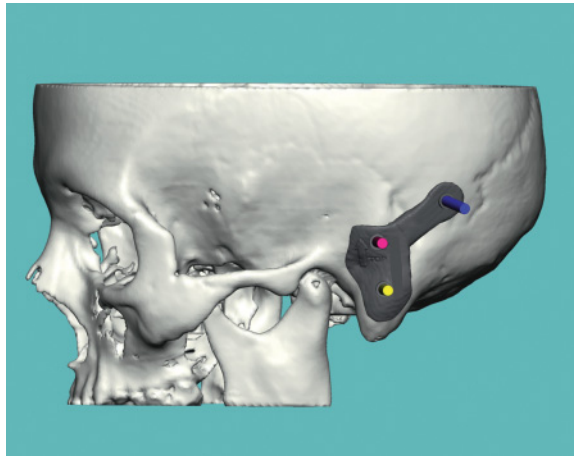


Figure 15.3 The final surgical guide design.

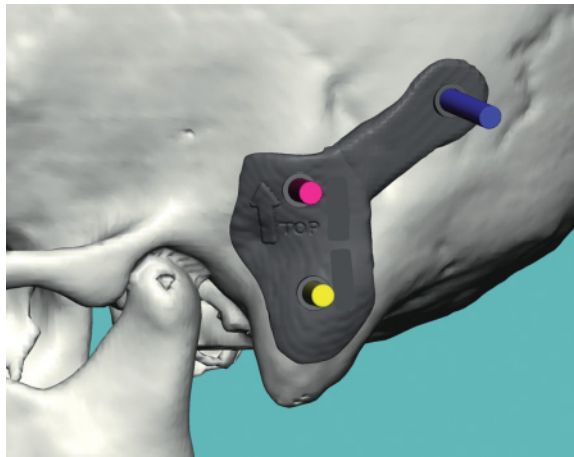


Figure 15.4 Close-up view of the final surgical guide design.

the necessary drilling locations. Digital design tools were also used to create embossed features on the surgical guide. The areas surrounding the holes were made deeper, and an orientation arrow was added to aid location during surgery. As a precaution, the patient's name was also engraved onto the part. The guide design is shown in Figure 15.3, with a close-up view in Figure 15.4. The patient's name has been obscured from these figures to preserve anonymity.

Finally, when the design was completed to the clinicians' satisfaction, the bone data were subtracted from the surgical guide as a Boolean operation. This left the rear surface of the surgical guide as a perfect fit with the anatomic surface of the bone. The final design was then exported as a high-quality .stl file for manufacture using selective laser melting (SLM).

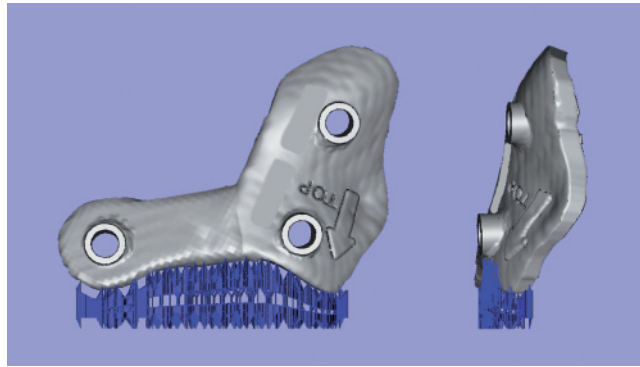


Figure 15.5 The .stl file of the guide with its supports.

Step 3: Guide manufacture

SLM is a layer-additive manufacturing process that enables solid metal objects to be built directly from 3D computer data. The machine used in this case was an SLM 250 (MTT Technologies Ltd, Stone, Staffordshire, UK). The process works by splitting the 3D computer model (in this case the .stl file of the guide) into a series of thin cross-sections called layers.

The SLM machine then creates the first layer by drawing the cross-sectional area onto the surface of a bed of very fine metal powder with a high-energy laser (the machine in this case being equipped with a 100W fibre laser). The energy from the laser causes the metal particles to melt, which forms a solid metal cross-section. The powder bed is then lowered by one layer thickness, and fresh powder is spread over the previous layer. The next layer is then drawn, melting the powder to form the next cross-section, while the heat penetrates deep enough to cause the layer to fuse to the previous layer. The process continues until the whole part has been completed. When the build process is finished, the part is removed from the unused powder and cleaned ready for its intended purpose. The inherent risk of fire or explosion resulting from handling fine powders is controlled by purging the build chamber with Argon gas.

In order to successfully build the surgical guide using SLM, supports had to be created. Supports provide a firm base for the part to be built onto while separating the part from the substrate plate. In addition, the supports conduct heat away from the material as it melts and solidifies during the build process. Inadequate support leads to build failure. The surgical guide was oriented such that the amount of support necessary was minimized and avoided the fitting surface of the guide (Figure 15.5; the patient's name has again been obscured to preserve anonymity). The guide was built using a layer thickness of 0.050 mm in 316L stainless steel powder.

Step 4: Finishing

Supports were removed using a hand-held power tool, and the guide was bead-blasted to leave a smooth, matte surface finish (Figure 15.6). The part was then sent to the hospital for cleaning and sterilization by autoclave.



Figure 15.6 The finished stainless steel guide.



Figure 15.7 The guide being test fitted to the stereolithography model in the laboratory.

Step 5: Evaluation

In the maxillofacial laboratory, the SLM surgical guide was test fitted to a stereolithography model of the patient's anatomy to ensure a precise fit to the required area (Figure 15.7). The guide was assessed and checked by the clinicians to ensure that it accurately represented the surgical planning before proceeding to surgery.

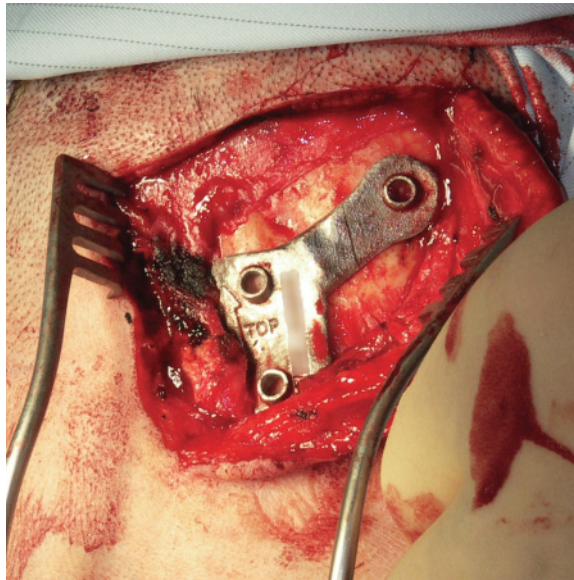


Figure 15.8 The guide in location during surgery.

There were no problems experienced in sterilizing or using the guide. Prior to surgery, the guide was again test fitted to the stereolithography model. When fitted in the intended location, the guide displayed good accuracy and fitted as expected. When seated on the anatomy, the guide located positively and securely and resisted movement, indicating a precise fit between the guide and the anatomy. The use of stainless steel enabled the guide to be made much thinner while maintaining excellent stiffness. This enabled some of the guide to be tucked under the soft tissue, which enabled a smaller incision to be used. This can be clearly seen in Figure 15.8. This results in reduced scarring and quicker recovery. The guide resulted in some time savings in theater but, much more importantly, enabled the surgery to be carried out with much greater accuracy and with a much better outcome for the patient.

The time and cost of guide production was comparable to previous RP methods such as stereolithography. Time and cost savings were realized by the use of autoclave sterilization rather than alternative low-temperature methods.

PROSTHESIS CONSTRUCTION

The 3D data of the ear were also used to aid production of the ear prosthesis. The mirrored .stl file of the remaining healthy ear was used to produce a wax model using a ThermoJet RP machine (3D Systems Inc, Rock Hill, SC, USA). The wax material is comparable to the wax typically used in the maxillofacial laboratory; this enabled the prosthetist to remodel and shape the wax pattern to fit the defect site using their usual techniques. Fine details, a substructure, and retention clips were added, and a stone mold was created from the wax pattern. The final silicone rubber prosthesis was molded, finished, and fitted to the patient in the usual manner.²⁶ The use of the mirrored wax model ensured a good match with the

contralateral healthy ear and also saved the prosthetist the time it would have taken to carve the basic ear form.

To date, SLM surgical guides have been utilized in 12 research cases undertaken by the Centre for Applied Reconstructive Technologies in Surgery (South Wales, UK). These cases have included six drilling guides for osseointegrated implant placement for prosthetic retention (as illustrated in this example) and two combined cutting and drilling guides for mandibular distraction. In addition, more complex combined drilling and osteotomy guides have been designed and used in four maxillary distraction osteogenesis cases.

The successful case studies have demonstrated that SLM is a viable method for the direct production of maxillofacial surgical guides for both osseointegrated implant placement and osteotomies. The stainless steel surgical guides produced using the SLM process have been shown to be comparable in terms of accuracy and quality of fit to the surgical guides previously produced using other RP processes, while demonstrating much improved physical properties. The time and cost of manufacturing the guides using SLM is also comparable to that of other RP processes.

CONCLUSION

The case studies have confirmed that SLM surgical guides can realize benefits compared with other RP methods. The SLM guide described in this case study demonstrated superior rigidity and much enhanced wear resistance. This enabled the guide to be thinner and smaller, which in turn led to the benefits of a smaller incision. The use of stainless steel also eliminated any secondary process to incorporate local reinforcement around the drilling holes as is the case with stereolithography surgical guides, saving time and cost. Another significant benefit is that the stainless steel guide was more convenient and more cost-effective to sterilize using standard autoclave procedures. The osseointegrated implant placement guides produced so far in this research have proved very successful and presented no major difficulties in terms of design, manufacture, or use in surgery.

ACKNOWLEDGMENTS

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Part 3

Movement and Facial Dynamics

16

Assessment of Facial Movement

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INTRODUCTION

Traditional craniofacial imaging techniques used in clinical assessment, diagnosis, and treatment planning include lateral cephalometry, photography, and more recently laser scanning and cone beam computed tomography. These techniques provide a static image of the facial structure and as such give a snapshot of static information at a given point in time. However, in most everyday life scenarios, we engage in functional activity. Although static imaging techniques continue to be routine in clinical practice, the focus is beginning to switch to imaging techniques that can accurately record and quantify facial movement.

Typically, dynamic facial movement has for the most part, received particular attention from the computer gaming, film and animation industries. However, three-dimensional (3D) facial movement can be of value to many clinical specialties, for example orthodontists, craniofacial surgeons, psychologists, and speech and language therapists. Specific clinical applications of facial movement would include the evaluation of functional surgical outcomes (e.g., following cleft lip and palate surgery and orthognathic surgery), the assessment of patients with motor nerve defects (e.g., facial nerve palsies), and the evaluation of psychomotor function associated with depression or pain. Facial expressions of emotion are also increasingly being used in neuroscience as probes for functional imaging and as stimuli for studying hemispheric specialization for face- and emotion-processing.

The technique of quantifying facial movement can be broadly termed “facial motion analysis/capture” or “dynamic facial imaging” and encompasses a variety of modalities from simple grading scales through to high-specification 3D imaging systems. Some of these systems have been labelled as “4D,” and may record sound as well as image data over time. A classification of techniques to analyze facial movement is proposed in Table 16.1.

Table 16.1 Motion analysis systems

Classification	Technique	Example
Grading scales	Subjective Objective	House–Brackmann Facial Nerve Grading System Facial Nerve Function Index
2D	Photography Cine camera	
3D	Passive-marker tracking Active-marker tracking Marker-less	FACIAL CLIMA Lip Function Monitor 3D Video (OGIS Research Institute) 3dMDface (3dMD) 4D capture (DI3D)
Other	MRI Facial electromyography	MRI movies

2D, 3D, 4D, two-, three-, and four-dimensional; MRI, magnetic resonance imaging.

SUBJECTIVE GRADING SCALES

Attempts to describe facial movement were described as early as the nineteenth century but suffered problems due to the lack of precise techniques to measure the face. For example, photographing subjects during electrical stimulation of selected facial muscles allowed the changing appearance of the face on contraction of the facial muscles to be studied.¹ The reports, however, were essentially verbal descriptions of facial expression and did not attempt to characterize the entire face as a whole or to quantify selected facial expressions.²

The House–Brackmann Facial Nerve Grading System is a widely used subjective grading scale for reporting facial nerve paralysis (Table 16.2).³ Although the reliability of this system has been found to be high, large interobserver disagreements have been revealed.⁴ The main problem in an evaluation such as this is the lack of an objective measure of the spatial and temporal aspects of facial function.⁵

OBJECTIVE GRADING SCALES

An objective component was added to the House–Brackmann scale by measuring the movement of the eyebrow and corner of the mouth on both the side affected by facial nerve palsy and the normal side.³ The results can be expressed as a percentage of function, but the system is subject to examiner bias as no reference point is defined and placement of the measuring instrument is dependent on the observer.

A further objective scale, described as the Facial Nerve Function Index, uses a single expression, the broad smile, to represent facial function.⁶ The distance between the lateral canthi and the lateral oral commissure at rest is measured for the normal side and the side affected by facial nerve palsy separately. The same distances are measured with the broadest possible smile. The “at rest” distance minus the smile distance for the affected side is divided by the same calculation on the normal side and multiplied by

Table 16.2 House-Brackmann facial nerve grading system

	Description	Characteristics
I	Normal	Normal symmetrical function in all areas.
II	Mild dysfunction	Slight weakness noticeable only on close inspection. Complete eye closure with minimal effort. Slight asymmetry of smile with maximal effort. Synkinesis barely noticeable, contracture, or spasm absent.
III	Moderate dysfunction	Obvious weakness, but not disfiguring. Complete eye closure and strong but asymmetrical mouth movement with maximal effort. Obvious, but not disfiguring synkinesis, mass movement or spasm.
IV	Moderately severe dysfunction	Obvious disfiguring weakness, inability to lift brow. Incomplete eye closure and asymmetry of mouth with maximal effort. Severe synkinesis, mass movement, spasm.
V	Severe dysfunction	Motion barely perceptible, incomplete eye closure, slight movement corner mouth. Synkinesis, contracture, and spasm usually absent.
VI	Total paralysis	No movement

100, yielding the Facial Nerve Function Index. The system is simple, straightforward, and objective but lacks any information about velocity, acceleration, or synkinesis. It also has built-in observer error as it lacks a fixed reference point.²

TWO-DIMENSIONAL MOTION ANALYSIS SYSTEMS

Although objective components have been incorporated into grading systems, many are still field-specific (i.e., primarily for the assessment of facial nerve defects) and therefore not appropriate for broader applications. In the 1990s, the development of modified two-dimensional (2D) imaging systems based on either photographs or cine camera films began the move towards true objective analysis of facial function.

Photographing subjects at maximal animation and at rest can quantify facial movement by measuring the amplitude of facial landmark motions.⁷ Physical markers are worn on selected landmarks and an adhesive ruler must be incorporated to allow for magnification error and measurement calibration. Although allowing quantification of movement in all regions of the face simultaneously, the 2D nature of the system means there is no representation of the actual path of motion of the facial landmarks.⁸

Cine cameras overcame the limitation of photographs and have been used to quantify the 2D trajectories of various lip landmarks during natural smiling and to report both the amplitude and the direction of the landmark motions.⁹ Ultimately, the limitations of 2D imaging in representing a 3D structure are well documented, and similarly when measuring amplitudes, it has been reported that 2D measurements can significantly underestimate 3D amplitudes.¹⁰

THREE-DIMENSIONAL MOTION ANALYSIS SYSTEMS

Motion capture systems are an established technique used in the field of gait analysis. They provide kinematic (measurement of the movement of the body in space) and kinetic (on the forces involved in producing the movements) information. Landmarks are placed on anatomic points and “tracked” during movement using multiple cameras. As the subject moves (e.g., walks on a treadmill), trajectories of the markers are calculated in 3D, thereby providing 3D motion analysis. In gait analysis, this information usually concerns joint mobility. More recently, 3D facial motion capture systems have evolved by means of the same principle.

There are, however, different demands and approaches between facial motion and body motion capture. With body motion capture, the movements of a structured bony framework are analyzed, which primarily involve generic, fluid movements. Facial motion capture on the other hand has a wider range of movements and expressions, and in addition lifelike nuances and subtle variations. These movements are often less than a few millimeters and therefore require greater resolution and fidelity than are usually used in body motion capture.

Nonetheless, the main systems that have dominated the field of facial motion capture are the “marker-based tracking systems,” which are similar to body motion capture systems. Using the concept of stereo-photogrammetry, they consist of groups of one or more cameras that are connected to a computer and track multiple landmarks placed on the subject’s face. Several of these systems have been described as in-house developments using either “passive-” or “active-”based markers.

Passive marker-based tracking systems

Passive marker-based systems use markers coated with a retroreflective material to reflect back light that is generated near the cameras lens. The camera’s threshold can be adjusted so only the bright reflective markers will be sampled, ignoring skin and fabric. The facial markers can vary in diameter from between 2 and 6 mm, can number up to 30, and are placed on specific facial landmarks.

To obtain 3D coordinate data for a marker, two cameras must record the marker’s position in space. As markers on the face may be carried outside the field of view of the two primary cameras, additional cameras can be used to ensure that data from at least two cameras are always recorded. Prior to recording facial movements, the cameras must be calibrated by way of an object with an array of markers whose positions in space are certified to a known accuracy.

For example, C3D (Glasgow Dental Hospital/Faraday Laboratory, University of Glasgow, UK) is a stereo-photogrammetric camera system¹¹ based on two pairs of video cameras placed either side of the subject with integral illumination. Preliminary investigations with the system using a dummy head indicated that it had an accuracy of 0.1 mm.¹² The main study recruited subjects who were highlighted with 20 landmarks on their face. Images were captured while performing a sequence of five facial expressions (rest, natural smile, maximal smile, lip purse, and maximal cheek puff) while maintaining natural head posture. The authors concluded that the extent of facial expression reproducibility was expression-specific and that differences existed between males and females.

The Motion-Analysis system (Motion Analysis, Santa Rosa, CA, USA) uses analog video cameras with a focal length of 25 mm to capture data at a sampling rate of 60 frames per second (fps). Spherical retro-reflective markers of between 2 and 4 mm diameter were attached to designated facial landmarks on subjects. Subjects performed a variety of maximal facial animations including smile, lip purse, cheek puff, eye closure, eye opening, and grimace. Among the findings of these particular studies has been the modeling of facial movement in patients with cleft lip and palate,¹³ the influence of gender and facial

shape in the 3D analysis of facial movement in normal adults,¹⁴ and the dynamic analysis of differences caused by orthognathic surgery.¹⁵

Vicon (Vicon 250; Vicon Motion Systems, Oxford, UK) tracks the motion of 2mm reflective markers placed on the face at 60fps using five infrared video cameras, and has been used to quantify spontaneous facial motility in infancy.¹⁶ Four separate reference markers were placed on the forehead to correct for head movement that would otherwise be included in the facial movement signals. Image-processing software identified the marker locations in each 2D infrared camera image to compute its 3D location relative to a calibration plate that was positioned in the data collection room. The system has been documented for its usefulness in research applications,¹⁷ but has also been reported to be too complicated for daily clinical application.¹⁸

FACIAL CLIMA (Sports Training Technologies, S.L., San Sebastian, Spain) has been described most recently; this uses marker-based tracking with infrared cameras on healthy subjects and has been proposed in the assessment of the functional outcome of facial paralysis reanimation surgery.¹⁹

Active marker-based tracking systems

Active marker systems use markers that are triggered by an incoming infrared signal and respond by sending out a corresponding signal of their own. This signal is then used to triangulate the location of the marker. The advantage of this system over the passive is that individual markers can work at pre-defined frequencies, and therefore have their own “identity.” This means that the post-processing of marker locations is minimized.

One such system is described as the Lip Function Monitor (University of Kent, Canterbury, Kent, UK). It uses a face mask mounted with infrared light-emitting diodes (LEDs) on one side and photodiode light detectors on the other. Direct coupling means that when the mouth is closed, the detector cannot “see” the emitters as its path is blocked by the lips. Conversely, when the mouth opens, the detector is incident upon the emitter. The photodiode circuits convert the infrared emission to an output of voltage that can be extrapolated on computer.²⁰

This technique gives a continuous, instantaneous readout of the movement of the LEDs, but is only suitable for extraoral use. Although a signal can be picked up for an intraoral LED, the signal becomes corrupted as it penetrates the soft tissue.²¹ Another limitation is that the wires connecting the LEDs to the power source have to pass between the lips, which may directly interfere with normal speech.

Although marker-based systems have been widely used in dynamic facial analysis, one of the main problems is the error introduced by placement of the landmarks between two different sessions. Systems devoid of markers solve this limitation, and indeed some of these so-called “marker-less systems” have now become commercially available and represent the latest developments in the field of 3D facial motion capture.

Marker-less systems

A relatively early study implemented videotaping to record facial movement without the use of facial markers. The video-recording was digitized, and absolute pixel counts were subtracted from sequential frames from the baseline frame to give computer generated x - y plots of relative facial movement.¹⁵ The results recommended the development of computerized systems to analyze facial movement as they enabled objective disease profiles to be constructed. It was not possible to create these profiles when subjective grading scales were used.¹⁶

3D Video (OGIS Research Institute Co Ltd, Osaka, Japan) is a 3D computer imaging program that has been used to analyze the motion of the lips.²² The hardware system consists of three infrared digital video cameras, one color digital video camera, a synchronizing signal generator, two distributors of the signal, an infrared projector, four digital video recorders, and a personal computer.

Following calibration of the cameras using a checkerboard cube, an infrared pattern is projected onto the subject and images recorded through infrared cameras at 30 fps. Lip motion is analyzed by dividing the upper and lower vermillions into four areas. The upper vermillion consists of five manually placed landmarks and one Bezier curved line, with the lower consisting of two landmarks and two Bezier curved lines. Following manual fitting of the Bezier lines, a virtual grid is made over the lips that allows shift and velocity during lip motion to be calculated in each area.²² By applying a template-matching technique, range images can be produced across the whole images during motion. Recently, this group applied the method to analyze the lip motion of patients with a cleft palate before and after surgical repair.²³

There are currently two commercially available marker-less 3D motion analysis systems, the 3dMDface Dynamic System (3dMD, Atlanta, GA, USA) and the 4D Capture System (DI3D; Dimensional Imaging, Glasgow, UK). These can be considered as true 3D facial motion analysis systems as their output data reconstruct the 3D facial geometry. In this respect, shape, volume, and surface topology can be objectively assessed.

3dMDface Dynamic System

The 3dMDface Dynamic System is based on active stereo-photogrammetry using a random infrared speckle projection. The latest-generation system is a six-camera, two-pod system comprising of six 1.3 megapixel cameras – four gray scale and two color (Figure 16.1). It can capture static images as well as sequential imaging at 60 fps. The output files are 3D geometry definition files (.tsb and .obj) that are



Figure 16.1 3dMDface Dynamic Imaging System (3dMD, Atlanta, GA, USA).

generated as one continuous point cloud produced from the two stereo camera viewpoints. The continuous point cloud can theoretically eliminate the data errors associated with merging/stitching datasets together from separate cameras.

Distortion of the infrared speckle as it projects onto a subject's face allows the generation of 3D coordinates of the face through complex algorithms. Several thousand points make up the cloud for a 3D image of the face. The .obj file format is a simple data-format that represents 3D geometry alone (i.e., polygons), namely the position of each vertex, the texture coordinate associated with a vertex, the normal at each vertex, and the faces that make each polygon.

White light is used to capture color texture images of the face simultaneously with the infrared pattern-produced 3D data. Small infrared components of the white light may have the potential to drown some of the infrared speckle pattern and therefore compromise image capture. The use of cold-illumination in the form of two Bowens Tri-lites (Bowens International Limited, Milton Keynes, UK) can minimize this effect.

4D Capture System

The passive stereo-photogrammetric 4D Capture System from DI3D uses a stereo pair of low-noise monochrome cameras to capture 3D shape, and a single color camera to capture the color texture images using only regular white light projection. The specification for the standard 4D system from DI3D is a three-camera, single-pod one comprising two 2 megapixel gray scale cameras and one color camera functioning at 30 fps. Their latest high-performance 4D system is also a single pod with two 4 megapixel gray scale cameras functioning up to 60 fps (Figure 16.2). Two-pod versions of both DI3D systems are also available.

Other three-dimensional motion analysis systems of relevance

Magnetic resonance imaging movies

Researchers have aimed to take advantage of the noninvasive and nonirradiative features of magnetic resonance imaging and adapt the system to dynamic imaging techniques. As the subject is not irradiated, it is practically and ethically possible to obtain images in multiple dimensions and on multiple occasions. Furthermore, dynamic MRI images allow repetitive images to be obtained with subtle changes in articulation associated with alterations in, for example, mandibular opening and advancement.²⁴

The first dynamic MRI images during motion, a so-called MRI movie, were used to record articulatory movement using the synchronized sampling method while a normal subject repeated a short utterance.^{24,25} More recently, MRI movies have been used to compare dynamic changes in the oropharyngeal structures of a normal subject and a subject with cleft lip and palate during the articulation of plosive target sounds.²⁴

An external trigger pulse was fed 128 times to the MRI scanner at 2 second intervals. Each pulse signaled the MRI scanner to start scanning. Subjects repeated the target sounds in whispers 128 times over 256 seconds while the run was measured using a fast spoiled gradient-echo (GRE) MRI sequence. A preprogrammed tone burst generated by a personal computer was delivered through a loudspeaker to synchronize the subjects' utterance to occur immediately after the trigger pulse. Following spatial interpolation of each image, free software for noncommercial use was used to display the resulting MRI images sequentially, resulting in the movements of the oropharyngeal structures being visualized as a movie.

The authors found that the synchronized sampling method used can show more realistic gestures of the oropharyngeal structures involved in dynamic articulation.²⁴ However, despite the fact that this



Figure 16.2 4D Capture System (DI3D: Dimensional Imaging, Glasgow, UK).

technique does offer simultaneous detection of the detailed movement of articulators without radiation, its limitation in requiring the subject to repeat a given syllable 128 times could lead to patient fatigue and detracts from its usefulness in children.

Facial electromyography

Neural activation results in the release of acetylcholine at motor neuron end plates in striated muscles, producing muscle action potentials, which can be measured by electromyography. Activation of the facial muscles produces dynamic as well as configuration information about neuromotor processes underlying rapid facial signals.²⁶ Short or low-intensity changes in these discharges can occur without producing feature distortions on the surface of the face, which enables electromyography to measure activity that might not be visible, and therefore not be a social signal. The activity of individual muscle strands can be measured by inserting needle electrodes into tissue, but this method can be painful, time-consuming, and highly intrusive.

ASSESSMENT OF FACIAL MOVEMENT

Much of the previous work that has been described has used either verbal facial gestures (i.e., speech) or nonverbal facial gestures (i.e., facial expressions) to assess facial movement. Many groups have published standard datasets that are freely available to the community.^{27–29} Nonverbal databases include facial expressions such as happiness (smiling), surprise (eyebrow raising), disgust (mouth opening), and sadness (frowning). Verbal databases can include any form of speech, with some examples being the uttering of digits “0” to “9,” and spoken phrases such as “Joe took father’s green shoe bench out.”²⁹

In principle, any facial gestures can be employed for the assessment of facial movement gestures. However, facial gestures that may be appropriate for use in psychology assessments may not be so for assessment in speech and language therapy. One must therefore consider the application carefully. Nonverbal databases tend to be more common than verbal ones, and they are often used in the computer science industry for animation and in psychologic evaluations to discern emotive behavior. Clinicians such as orthodontists and craniofacial surgeons may be particularly interested in how the region around the oral cavity moves.

Verbal facial gestures may be more appropriate in this setting as they are able to test lip articulation. Verbal gestures recommended in cleft speech assessment include speech postures that involve articulation of both the upper and lower lips, that is, bilabial speech postures, for example “The puppy was playing with the rope” and “Bob is a baby boy.”³⁰ An important consideration when analysing verbal facial gestures is that higher frame capture rates (48 fps and above) are preferential to adequately capture high-frequency distinct speech sounds, many of which have a duration of only 20 milliseconds.²⁰

The 3dMDface Dynamic Imaging System has been used in preliminary studies to assess facial movement during a standardized smile expression and the verbal facial gesture /puppy/.³¹ For a given sequence of facial movement at a specified number of frames per second, a series of sequential geometry file formats is obtained (Figure 16.3).

The resting frame is designated as the reference or baseline frame, and each remaining frame is surface-matched on nonmoveable points within the 3D point cloud. This is carried out individually for consecutive frames with the reference under a tolerance of 0.5 mm. This allows very little error in the alignment of two or more objects. Color deviation maps of the differences (in millimeters) between the two objects then enable quantification of the changes in facial movement over time (Figures 16.4–16.7).

When using a surface-matching technique such as this to quantify facial movement, there must be some stable areas on the face to allow for accurate superimpositions. A small error in alignment of the forehead can lead to larger errors in other regions of the face. Indeed, it has been shown in this preliminary study that there are insufficient areas that remain stable on the face to accurately assess facial

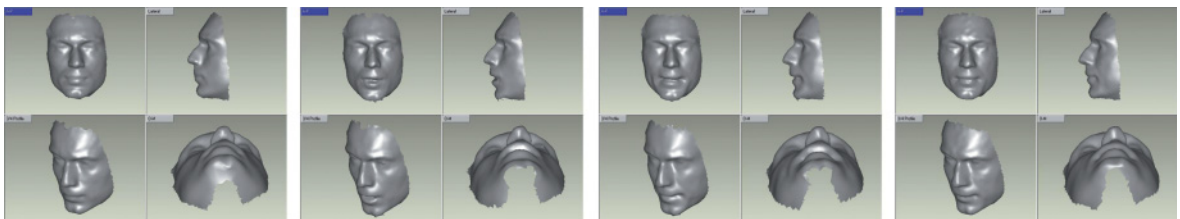


Figure 16.3 Selected frames from a sequence of facial movement using the verbal facial gesture /puppy/. (Left to right) Frames at T0, T5, T20 and T33 (T = 0.02 second).

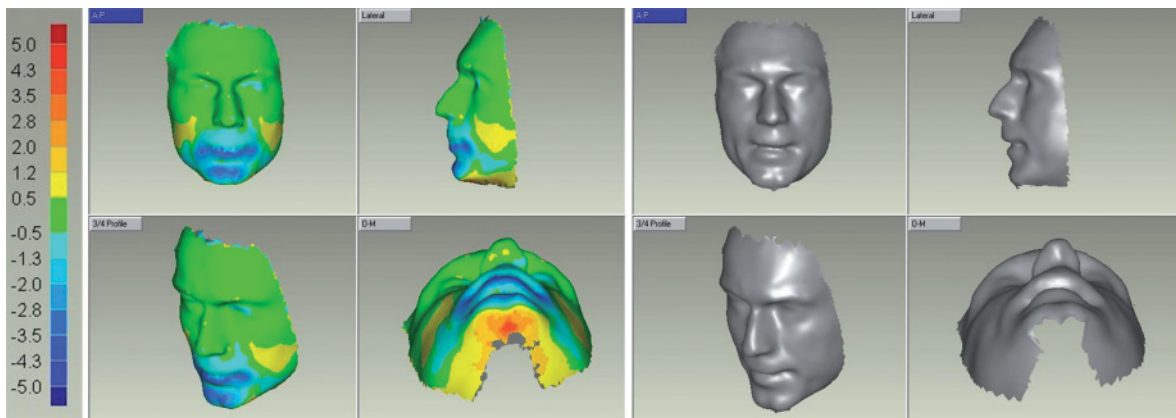


Figure 16.4 Color deviation map of the verbal facial gesture /puppy/ at T20 ($T = 0.02$ second) showing facial changes primarily affecting the lower half of the face. Strong positive changes (up to 5 mm) are seen in the region that corresponds with the zygomaticus muscles overlying the maxilla as they contract to bring the lips upwards. The regions corresponding to the upper lip and depressor anguli oris muscles flatten as they lift upwards, showing negative changes (up to -4.3 mm). Note that there is very little movement in upper half of the face (± 0.5 mm). The blue range shows increasing intensity to negative changes, the red range increasing intensity to positive changes.

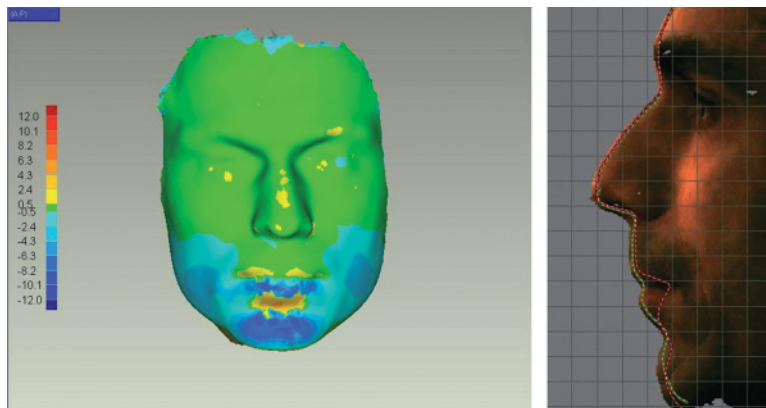


Figure 16.5 Color deviation map and mid-sagittal section of the verbal facial gesture /puppy/ at T5 ($T = 0.02$ second), showing the extent of the negative facial changes. The blue range shows increasing intensity to negative changes, the red range increasing intensity to positive changes.

changes during a sequence of facial movement using a standardized smile facial expression when compared with using spoken word.³¹

Other methods to analyze the dataset include the use of principal component analysis (PCA) to quantify the lip dynamics of a given sequence of facial movement.³² A description of the methodology behind this is beyond the scope of this text. However, we can say that PCA allows the representation of a sequence of facial movements in a numerical form whereby each frame corresponds to a set of numbers called Eigencoefficients or modes of variation (MoV). For example, the utterance “puppy” is

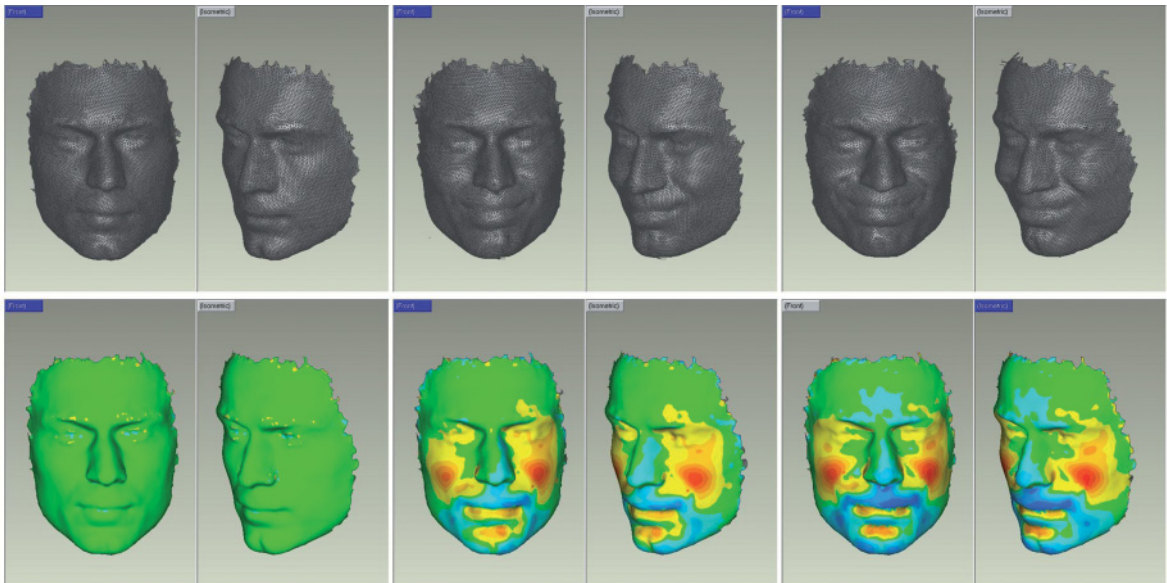


Figure 16.6 Color deviation maps of selected frames from a standardized smile expression sequence with corresponding three-dimensional surface images at T0, T10, and T17 ($T = 0.02$ second). Strong positive changes are seen affecting the zygomaticus muscles (up to 5 mm) overlying the maxilla as they contract to bring the lips upwards. The upper lip and depressor anguli oris muscles flatten as they lift, showing negative changes on the deviation map (up to -4.3 mm). Note that the majority of the facial surface is moving during this nonverbal facial gesture. The blue range shows increasing intensity to negative changes, the red range increasing intensity to positive changes.

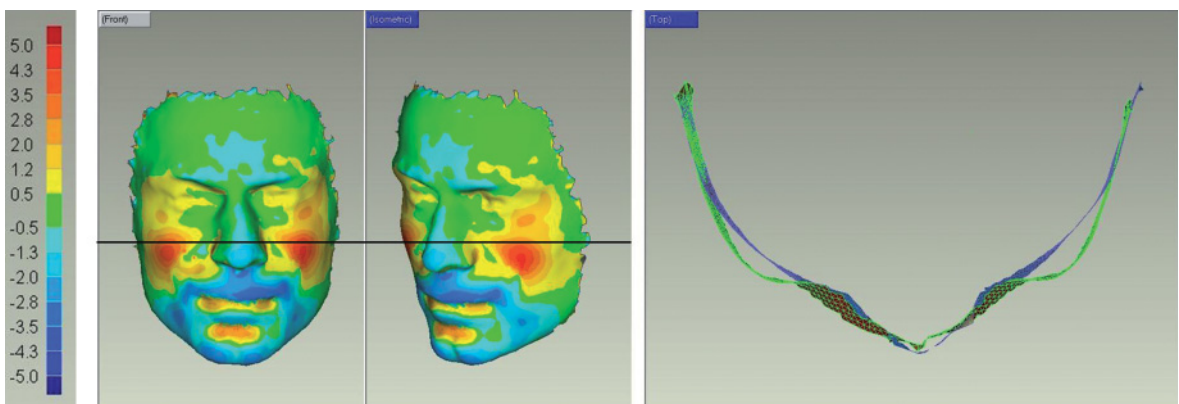


Figure 16.7 Coronal section taken through a color deviation map of T15 against reference T0 ($T = 0.02$ second). The section reveals good smile symmetry.

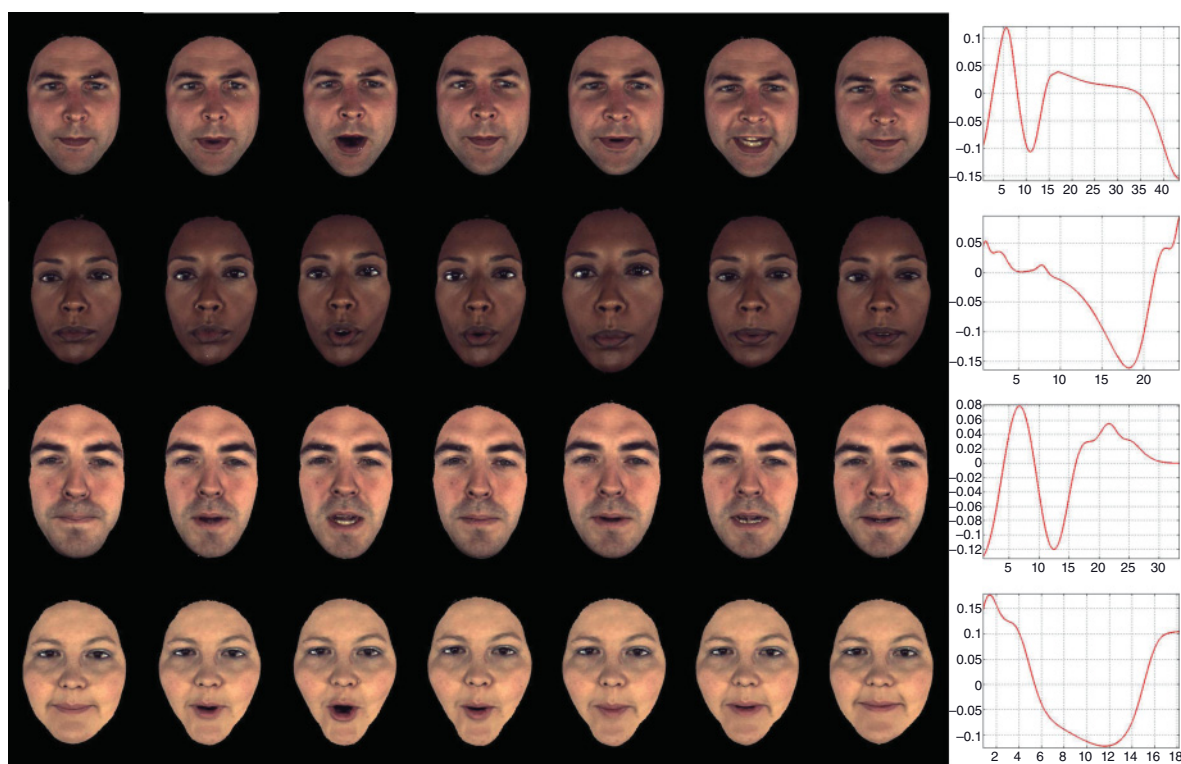


Figure 16.8 Lip dynamics showing the first mode of variation of the verbal facial gestures /puppy/, /rope/, /baby/, and /bob/. x-axis, frame number ($n = 0.02$ second), y-axis, standard deviation of lip movement.

a combination of several lip movements, such as lip opening, lip closure, lip stretch, etc. The PCA breaks the utterance down into several MoVs in which the first MoV represents the main variation or principal movement (Figures 16.8 and 16.9). In the case of the utterance “puppy,” the first MoV controls the lip opening and the second MoV will control the lip stretch. Higher-order MoVs will mainly constitute noise, and up to three MoVs are sufficient to describe the lip dynamics of spoken words.

Reproducibility of facial movement

A further consideration in deciding whether to use verbal or nonverbal facial gestures is how reproducible the gesture is. Reproducibility of head position is important in the assessment, diagnosis, and treatment planning of orthodontic and craniofacial procedures. Natural head position has been the standard adopted for static facial pose.^{33,34} With the advent of dynamic facial imaging, a reproducible measure of facial movement needs to be determined to allow an accurate assessment of changes in facial movement over time and following treatment procedures.

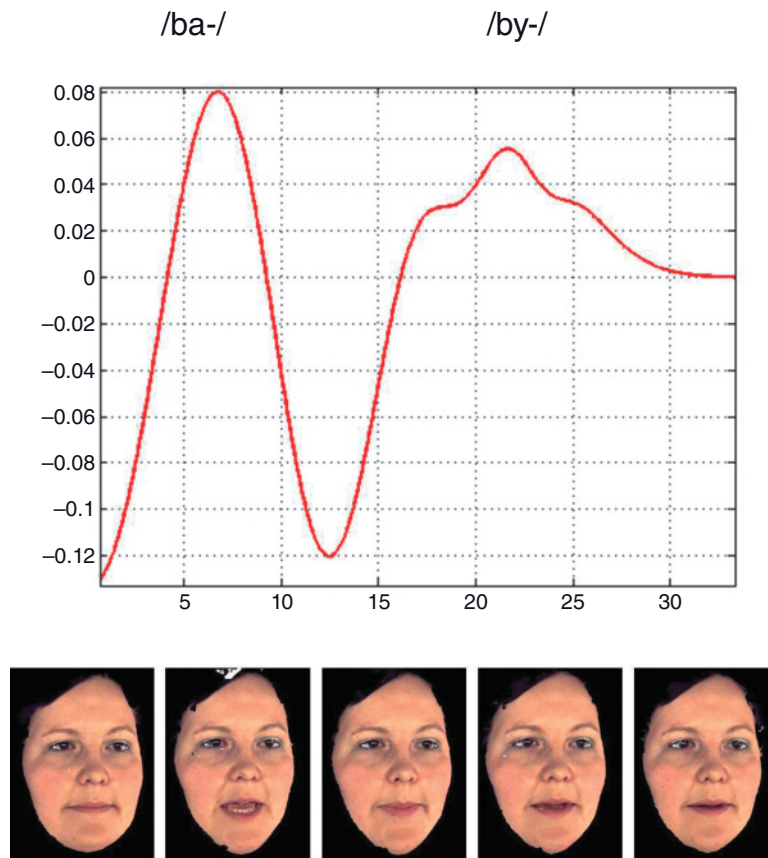


Figure 16.9 Interpretation of the lip dynamics of the verbal facial gesture /baby/ using corresponding facial surface images.

Previous work on facial expressions has shown that there is a hierarchy of expression reproducibility, with the rest position being significantly more reproducible than lip purse, maximal smile, natural smile, or cheek puff.¹¹ However, gender and age have been shown to affect facial dynamics, with the elderly and males showing larger facial movements in a study of healthy subjects, and this may affect the reproducibility.³⁵ It is also highly likely that the reproducibility of nonverbal facial gestures will be largely dependent on the mood of the subject, and as these movements often involve maximal displacements, facial fatigue is another limitation in their use.

Some research is now being published on the reproducibility of verbal facial gestures.^{32,36} Spoken words are very reproducible but can be dependent on the individual and the type of word used. Single-word gestures are preferred as they carry less emotion when compared with sentences, and single words are often the most natural way to evoke a facial movement response. The other advantage of using verbal facial gestures is in the field of speech recognition, whereby reproducible and distinctive words can be used to replace conventional keyboard passwords for security systems. Do words that

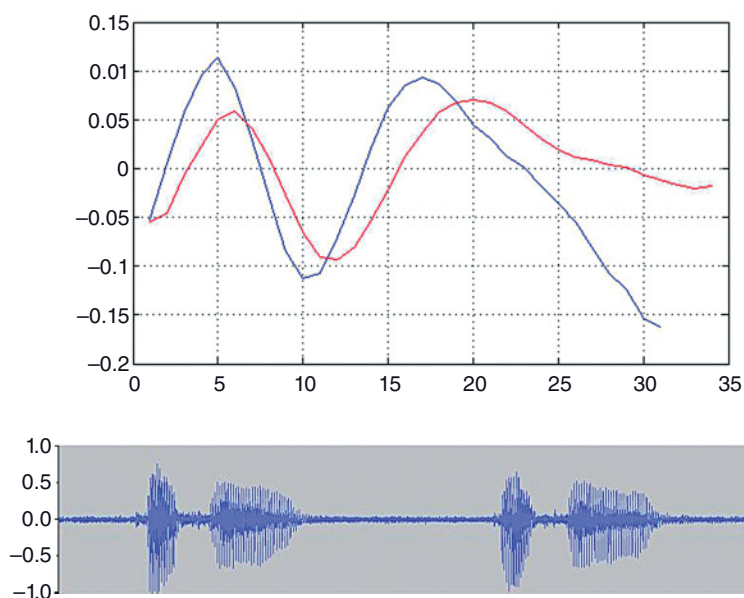


Figure 16.10 Lip dynamic of the verbal gesture /puppy/ shows very similar repetitions graphically. Audio-recordings of the separate utterances also show very similar frequencies.

are articulated similarly, sound similar? It is interesting to note that when verbal facial gestures are analyzed and found to be reproducible in their lip dynamics, the audio analysis is also very similar (Figure 16.10).

To determine whether facial movement during speech is reliable, a numeric value should be assigned to what is meant by reproducible. In other words, how much do repeated facial gestures have to vary before they are no longer considered reproducible? From a clinician's point of view, this figure should be as low as possible, and from the limited published research in this area, it would appear that age- and gender-specific reproducible measures rather than single generic ones should be identified.

CONCLUSION

Clinical facial motion capture is continuing to be an evolving field of research and practice. Although subjective grading scales are quick and simple to use in the clinical setting, 3D objective facial motion capture systems have become commercially available and are forming the "gold standard" in quantifying facial motion. Key points to note in the quantification of facial movement are that systems should be 3D in nature and output 3D geometry data so that surface volume and topology can be assessed. If verbal facial gestures are to be used, the frame capture rate of the system must be a minimum of 48 fps. As next-generation 3D motion capture systems are released and sophisticated software tools are written to analyze the data, clinical research will be able provide robust databases of normative facial movement and post-surgical functional outcome to be evaluated comprehensively.

Please refer to the supporting companion website at: www.wiley.com/go/kau

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17

Facial Actions for Biometric Applications

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INTRODUCTION

The face is the primary means for humans to recognize each other in everyday life, and although the human face is commonly used as a physiological biometric, very little work has been undertaken to exploit the idiosyncrasies of facial motions for computerized person identification. Previous studies such as Eigenfaces¹ and methods based on support vector machines² have inspired a number of two-dimensional (2D) face recognition solutions, which are now employed in various commercial and forensic applications, for example Viisage (L-1 Identity Solutions, Littleton, MA, USA) and Cognitec (Cognitec Systems GmbH, Dresden, Germany).³

Despite such wide acceptance, the face is commonly considered to be a weak biometric because it can display many different appearances due to rigid motions (e.g., head poses) and nonrigid deformations (e.g., facial expressions), and also because of its sensitivity to illumination, aging effects, and artifices such as make-up and facial hair.⁴

In terms of facial analysis, three-dimensional (3D) data often simplify some processes, such as head pose and illumination problems.⁵ However, dealing with facial expression variability still remains an open issue. Chang and co-workers⁶ have suggested using expression-invariant facial regions (e.g., the region around the nose) for identity recognition; another solution is to employ statistical model-based algorithms such as the 2D active appearance model⁷ (suitably extended to 3D) and the 3D morphable model,⁸ which can accurately interpret unseen facial poses thanks to a prior learning process.⁹

More recent research trends have started to consider facial expressions as an additional source of information rather than a problem to overcome. Pioneering work has reported very promising results in the contexts of speaker identification by lip-reading,¹⁰ speech/facial features,¹¹ and lip motion.¹² However,

little emphasis has been placed on examining in depth the characteristics of facial dynamics and their suitability for biometric applications, and several questions remain open:

- Are facial actions stable over long time intervals?
- How much do they vary with the subject's emotional and physical conditions?
- Are they sufficiently discriminative across a large population?
- Can we arbitrarily employ any facial expressions for identity recognition, or is there a hierarchy in their biometric power?

Studies have been designed to answer these questions, and investigations have been carried out to explore the *uniqueness* and *permanence* of facial actions to determine whether these can be used as a behavioral biometric.^{13–15} Work has been undertaken using 3D video data of participants performing a set of very short verbal and nonverbal facial actions. The data have been collected over long time intervals to assess the variability of the subjects' emotional and physical conditions. Quantitative evaluations are performed for both the identification and the verification problems, the results indicating that emotional expressions (e.g., smiling and disgust) are not sufficiently reliable for identity recognition in real-life situations, whereas speech-related facial movements show promising potential.^{13–15}

WHICH FACIAL ACTIONS MAKE A SUITABLE BIOMETRIC?

Is it possible that any facial actions can be considered for person recognition? In principle, this may be the case. However, choosing those which exhibit high biometric discriminative power is analogous to choosing strong computer login passwords over weak ones. It is also preferable to use *very short* facial actions to reduce the processing effort so that genuine users can gain access quickly to the secure services.

The majority of related work has been carried out using speech analysis,^{10–12} usually employing popular face databases for lip-reading and speech synthesis such as the M2VTS¹⁶ and the XM2VTSDB,^{16,17} which include audio–video data of continuously uttered digits from “0” to “9” and spoken phrases such as “Joe took father's green shoe bench out.” Also commonly used is the DAVID database,¹⁸ in which nine participants wearing blue lipstick utter isolated digits.

These databases have been designed for speech research purposes and are not suitable for biometrics. In fact, the use of physical markers is inconvenient for a real-life application such as biometrics, and furthermore, although long phrases are necessary for speech analysis, they require intensive processing effort, especially when 3D dynamic data are employed. Although one might consider using only short segments of the long phrases, such “cut-out” syllables are inevitably plagued by co-articulation effects, which unnecessarily complicates the problem at this early stage. For these reasons, we decided to collect a new set of *very short* and *isolated* facial actions.

VERBAL FACIAL ACTIONS

With regard to speech-related facial motions, one might be tempted to see a direct link with research on speech analysis, where the distinctiveness of lip motions has been studied.^{19,20} However, lip-reading and biometrics are two different problems. While lip-reading aims to recognize phonemes from lip shapes

Table 17.1 English language phoneme to viseme mapping²²

Viseme	Phoneme	Viseme	Phoneme
/p/	P	/k/	K
	B		G
	M		N
	EM		L
/f/	F	/t/	NX
	V		HH
/t/	T		Y
	D	/iy/	EL
	S		EN
	Z		IY
	TH	/aa/	IH
	DH		AA
	DX	/ah/	AH
/w/	W		AX
	WH		AY
	R	/er/	ER
/ch/	CH		EO
	JH	/ao/	OY
	SH		IX
	ZH		OW
/ch/	EH	/uh/	UH
	EY		UW
	AE	/sp/	SIL
	AW		SP

From P. Lucey, T. Martin and S. Sridharan, 2004, with permission from the authors.

(visemes) and must be speaker-independent, we seek on the contrary to recognize the visemic dissimilarities across speakers uttering the same phoneme. Another field where there has also been a great deal of interest in characterizing facial motions is orthodontics and craniofacial research. However, these studies often use a very small number of subjects (between five and 30) and examine limited speech postures,²¹ which is inconclusive for biometrics.

Our objective here is to assess, first, the repeatability of viseme production over time for any speaker, and second, the distinctiveness of lip motions across speakers. To this end, we will examine a set of words chosen among the visemes of the English language as depicted in Table 17.1.

The *point of articulation* plays a great role in the strength of a consonant. While bilabial consonants (involving the lips; e.g., /p/, /b/, and /m/) and labiodental consonants (upper teeth and lower lip; e.g., /f/, and /v/) are informative because their visible variations can be easily captured by the camera,

consonants involving internal speech organs such as the palate and the tongue (e.g., /t/, /k/, /r/, etc.) are expected to be poor because their variations are hidden.

Vowels typically form the nuclei of syllables, whereas consonants form the onsets (preceding the nuclei) and the codas (following the nuclei). A coda-less syllable of the form V, CV, or CCV – in which V stands for vowel and C for consonant – is called an open syllable, and a syllable that has a coda, such as VC, CVC, or CVCC, is called a closed syllable. The vowel of an open syllable is typically long, whereas that of a closed syllable is usually short. Two adjacent vowels in a syllable of the form CVVC usually behave as a long vowel. The r-controlled (vowel followed by “r”) and the l-e-controlled (consonant-l-e at end of syllable) are neither long nor short, but allow trailing, as in a long vowel.²³

Our comparative evaluation has been performed on different types of syllable, using the following words: “puppy” (CVC/CV, short vowel/long vowel), “baby” (CV/CV, long vowel/long vowel), “mushroom” (CVCC/CVVC, short vowel/long vowel), “password” (CVCC/CVC, irregular case: long vowel/r-controlled vowel), “ice cream” (VCV/CCVVC, long vowel/long vowel), “bubble” (CVC/CV, short vowel/l-e-controlled), “cardiff” (CVC/CVC, r-controlled vowel/short vowel), “bob” (CVC, short vowel), and “rope” (CVC, irregular case: long vowel).

NONVERBAL FACIAL ACTIONS

Unlike visual speech, which involves mainly lip motions, emotional expressions also involve movements of the forehead, the eyebrows, the eyes, the nose, etc. Thus, in order to accurately capture the idiosyncrasies of a person’s facial dynamics, the entire face needs to be analyzed. However, such a holistic approach may be computationally prohibitive. Therefore, it is useful to determine which facial regions are the most important to convey identity, so that we can analyze only the most informative part of the face. This question has already been investigated in perceptual studies, but these works were carried out on 2D still images rather than on 3D dynamic data, and there have been so far no convergent conclusions. Whereas Brunelli and Poggio²⁴ suggested that the mouth is the most discriminative facial feature across individuals, more recent studies indicate that it is rather the eyebrows, followed by the eyes, the mouth, and the nose.²⁵

We have examined a set of facial actions involving facial muscles. We have studied the basic emotions (e.g., smiling and disgust) along with a number of facial action units (AU) based on the Facial Action Coding System (FACS),¹³ for example brow raiser (AU1+2), brow lowerer (AU4), upper lid raiser (AU5), nose wrinkler (AU9), and lip corner puller (AU12). Interestingly, research in orthodontics and craniofacial research has found evidence that facial actions involving maximal muscle stretches are more reproducible than moderate expressions.²¹ Therefore, we have focused on facial expressions of maximum intensity only.

DATA ACQUISITION

To collect data on facial actions for our research, two 3D video cameras operating at 48 frames per second are employed (Figure 17.1). Although the cameras have been purchased from the same provider (3dMDface Dynamic System; 3dMD, Atlanta, GA, USA), they are of different generations, hence the 3D mesh densities and the texture qualities they produce are noticeably different. The recording sessions are carried out in two laboratories with different ambient conditions (daylight or dark room), and there is no strict control of the head position; small head movements are allowed as long as we ensure an ear-to-ear coverage of the face. No physical markers are used. Such settings resemble a real-life scenario where faces are



Figure 17.1 The 3dMDface Dynamic System (3dMD, Atlanta, Georgia, USA).



Figure 17.2 In different recording sessions with different people, participants are required to speak in a normal and relaxed way.

also expected to be collected from different data capture devices in different recording conditions. In this way, we can evaluate how well our recognition algorithm performs on data of variable quality that have been collected in moderately constrained environments (Figure 17.2).

The subjects were staff and students recruited within Cardiff University, UK. All were naïve users who have not been trained beforehand; in particular, none was familiar with the FACS.²⁶ The participants were asked to perform a number of basic emotions/expressions (e.g., smile, disgust) and a small set of AUs as described, targeting a maximal muscle stretch; on the other hand, they were also required to utter a set of *isolated words*, speaking in a normal and relaxed way.

The recording sessions were scheduled over long time intervals (ranging from a few weeks to over 2 years) to assess the variability of the subjects' emotional and physical conditions. We have been able to collect data from 94 participants (61 males and 33 females, 70 of whom were natural English speakers). The word "puppy" was studied in some subjects over 2 years. Fifteen participants were used to study other utterances (e.g., "password," "mushroom," etc.), and the repetitions were recorded over a period of 1 month maximum. The smile dynamic has been studied in 50 subjects, and smaller tests were conducted on FACS AUs.

FACIAL IDENTITY RECOGNITION

Many techniques have been proposed for extracting facial dynamic features, which do not require the use of physical markers. For example, the work of Pamudurthy and co-workers aimed to track the motion of skin pores,²⁷ whereas the work of Faraj and Bigun¹² used the velocity of lip motions for speaker recognition. These methods are interesting and novel; nevertheless, they still require more research. In this study, we adopt another feature-extraction approach relying on the well-established model-based algorithms used in static face recognition, for example the active appearance model⁷ and the morphable model.^{8,13–15} The data pre-processing and feature extraction steps are briefly outlined below.

Face normalization

One nontrivial preliminary task in face recognition is to normalize the scans so that they can be compared in the same coordinate frame (i.e., with a similar head pose and size). The normalization is achieved using a nose-matching technique proposed by Chang and co-workers;⁶ the result is illustrated in Figure 17.3. The nose root is found using 3D curvature analysis, and then the surface normal at the nose root

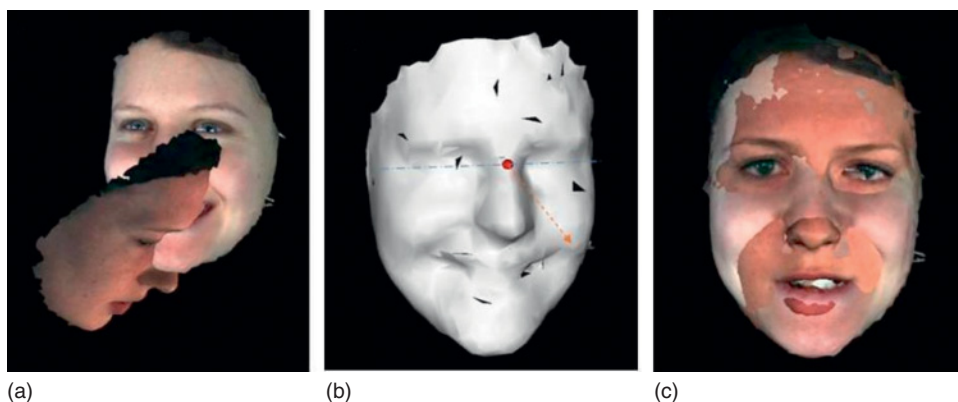


Figure 17.3 Rigid object three-dimensional registration. (a) Two raw face scans presenting different head poses and sizes need to be aligned. (b) The nose root is located, together with the eye directions and surface normals. (c) The alignment is achieved through rotations, translations, and scaling, and then refined by applying the iterative closest point algorithm to the nose region.

and the eye direction are computed. These quantities determine the adequate translations, rotations, and scaling to align the faces. Further refinements can be achieved using the iterative closest point (ICP) matching algorithm,²⁸ applied to the most stable regions around the nose root.

In practice, we use one video frame as the reference frame, and register all frames in the database to the latter. The choice of the reference frame is arbitrary as long as we employ one and only one reference for the entire database.

Frame correspondence and segmentation

One principal requirement in our statistics-based feature-extraction approach is that all face scans must be in full correspondence, that is, they must have the same number of vertices and identical vertex topology. However, our 3D data capture technology treats each scan as an independent problem, resulting in all meshes being uncorrelated. Therefore, one additional processing step is needed in order to bring all frames into correspondence, which can be achieved as follows.

The idea consists of choosing one face to be *the* reference frame for the entire face database, and using a thin-plate-spline warping process to deform this one to each of the frames in the database. This produces a new database in which all faces have the same vertex topology as the reference frame, but the facial expression of each frame is identical to that of the corresponding frame in the original database.

The purpose of the warping process is twofold. First, it brings all the frames into correspondence, and second, it permits the segmentation of the region of interest. For example, by using a lip shape as a reference template and deforming this one to the lip region of the target frames, we can produce a sequence of lip shapes in full correspondence, as shown in Figure 17.4.

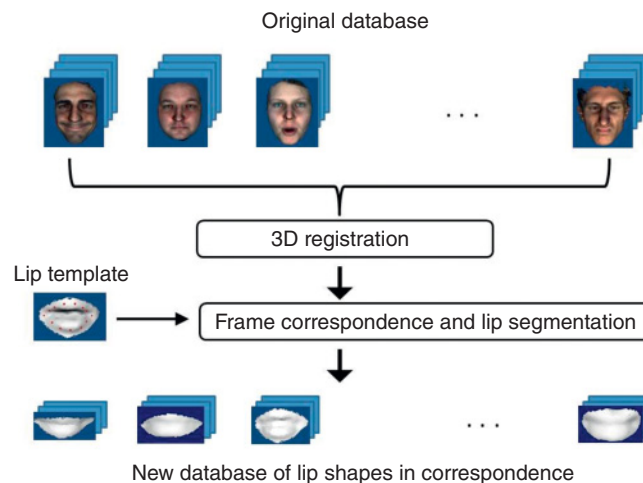


Figure 17.4 The warping process also permits the segmentation of the region of interest when using different facial templates. Here the lip segmentation is realized by using a lip template.



Figure 17.5 3D Active appearance model.

Facial dynamics: representation and extraction

After the above pre-processing steps, the face database is now divided into training set (gallery) and test set (probe). The gallery includes only one video sequence per subject due to limited data availability; the probe contains several repetitions for each subject. The gallery and probe are entirely distinct data segments, the probe including subjects enrolled in the gallery, as well as “unseen” persons. In this study, we typically build one model for each facial expression, which includes all subjects enrolled in the gallery.

Our statistical model of combined 3D shape and texture (Figure 17.5) is built in similar fashion to the 2D active appearance model,⁷ but the shape model includes the x -, y -, and z -coordinates of all vertices as in the morphable model.⁸ Figure 17.6 depicts the temporal variations of the first Eigencoefficient and the corresponding facial expressions of a subject performing the FACS Action Unit 9 (nose wrinkler).

The facial dynamics can be extracted from the variations of the 3D shape alone, independently of the texture information. Therefore, for the remainder of this study, we will build a simple 3D active shape model (3D ASM) instead of the complete active appearance model. For a more efficient face recognition approach (i.e., dimensionality reduction of the feature space and noise removal), we retain only 90% of the shape variations. Figure 17.7 shows the lip dynamics of four subjects saying “puppy.” The temporal variations of the first three Eigencoefficients ($v_k^1, v_k^2, v_k^3, k \in \{1, \dots, N\}$) are depicted.

MATCHING FACIAL DYNAMICS

Well-established algorithms such as hidden Markov models (HMM) and Gaussian mixture models are the preferred pattern-matching techniques employed in the previous work.^{10,12} However, it is unclear whether these statistical approaches would perform efficiently in the present context where we use only very short data sequences, and do not have many repetitions per subject to train an accurate HMM. For

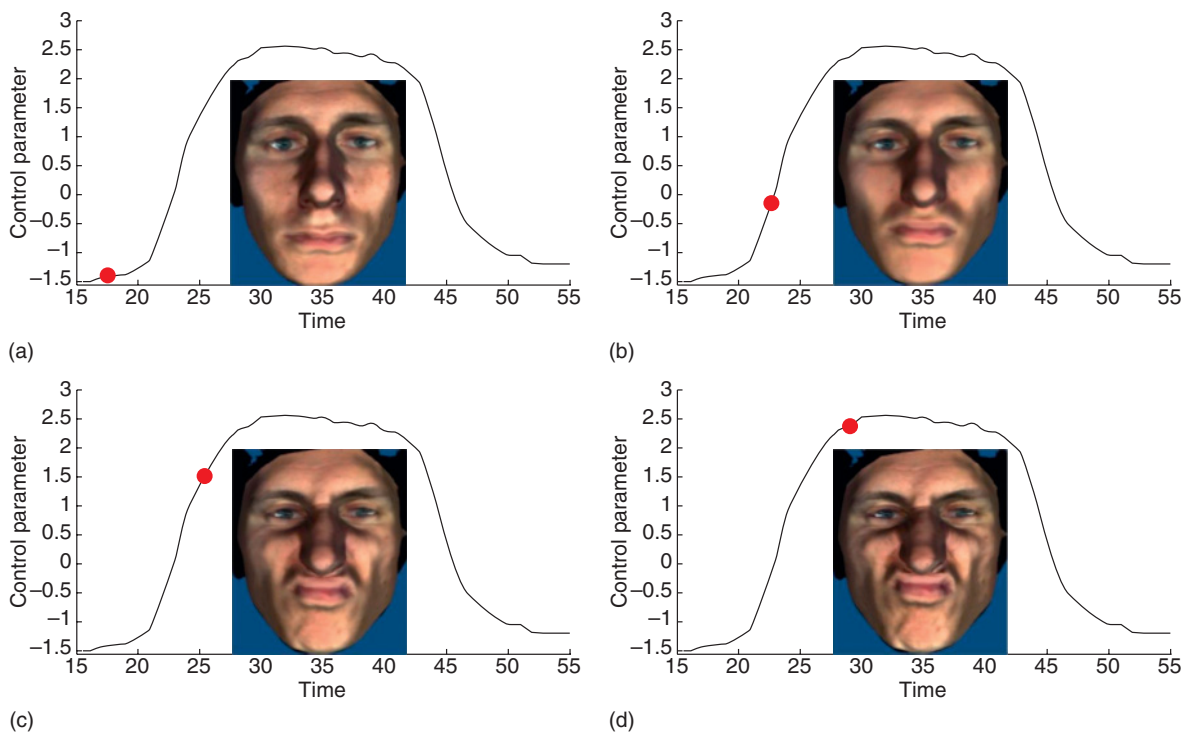


Figure 17.6 A subject performing a Facial Action Coding System Action Unit 9 (nose wrinkler) and corresponding temporal evolution of the first Eigencoefficient.

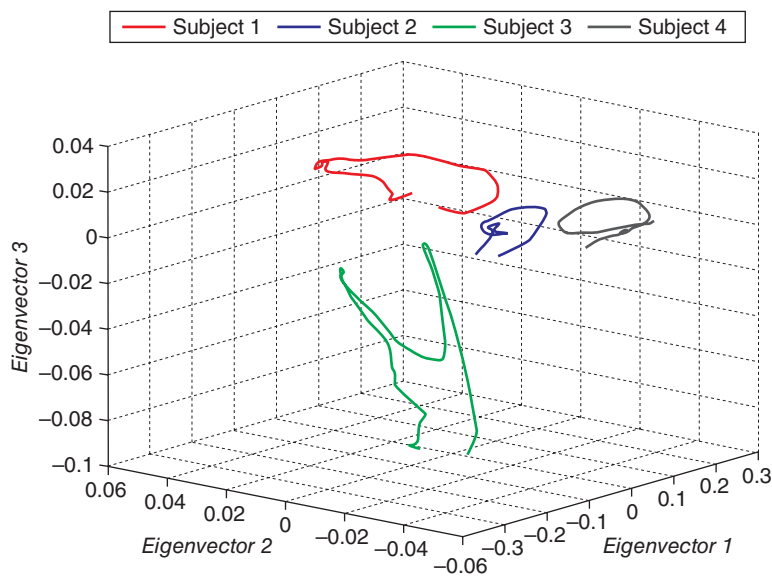


Figure 17.7 "Puppy" dynamics of several subjects in the feature space.

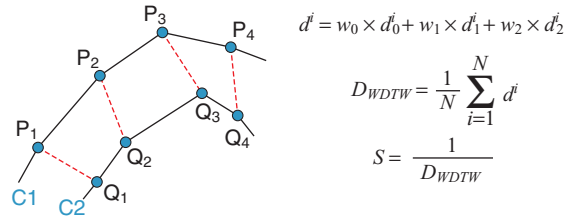


Figure 17.8 Weighted derivative dynamic time warping algorithm.

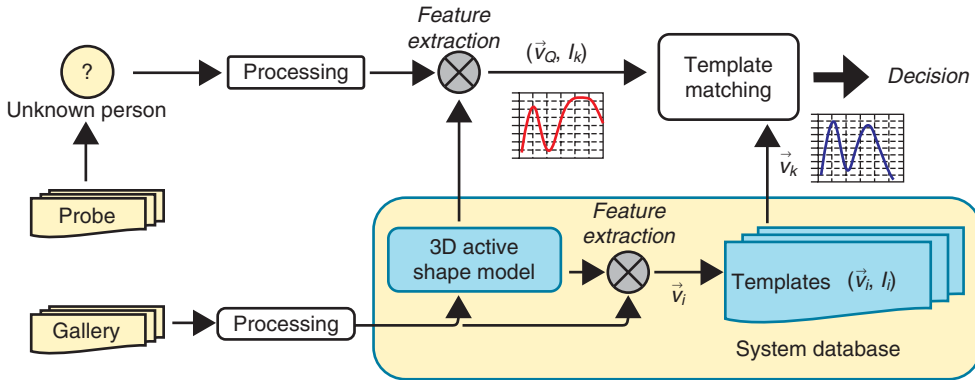


Figure 17.9 Architecture of the face dynamics matching prototype. Given a biometric feature vector v_Q of an unknown person and a claimed identity l_k , determine if the person is a genuine user or an impostor. Typically, v_Q is matched against v_k , the biometric template of l_k .

this reason, we surveyed a number of pattern-matching techniques commonly used in behavioral biometrics (e.g., voice and signature authentication) and evaluated which of these performed the best when applied to facial dynamic matching.¹³ Well-known methods such as the Fréchet distance,²⁹ correlation coefficients,³⁰ dynamic time warping (DTW),³¹ continuous DTW,³² derivative DTW,³³ and HMM¹⁰ were examined, in light of which we have proposed an improved algorithm weighted derivative DTW (WDTW) as follows.¹³

Suppose we have two feature vectors, which are respectively depicted by two sequences of discrete data points C_1 and C_2 , as shown in Figure 17.8. For each point P_i of C_1 , we compute its closest point Q_j on C_2 with respect to the distance $d^i = w_0 d_0^i + w_1 d_1^i + w_2 d_2^i$, where d_0^i is the Euclidean distance between P_i and Q_j , d_1^i is the difference between the local first derivatives, and d_2^i is the difference between the local second derivatives; w_0 , w_1 , and w_2 are weights. The distance D_{WDTW} between C_1 and C_2 is defined as the sum of all pairwise distances d^i , normalized by the sequence length N . Thus, the similarity between two feature vectors can be computed as $S = 1/D_{WDTW}$. The overall facial dynamics matching system is summarized in Figure 17.9.

We have investigated the use of facial actions for person recognition utilizing WDTW, which performs the best in the present context.¹³ A summary of the comparative evaluation of pattern-matching algorithms has been presented elsewhere.^{13,14}

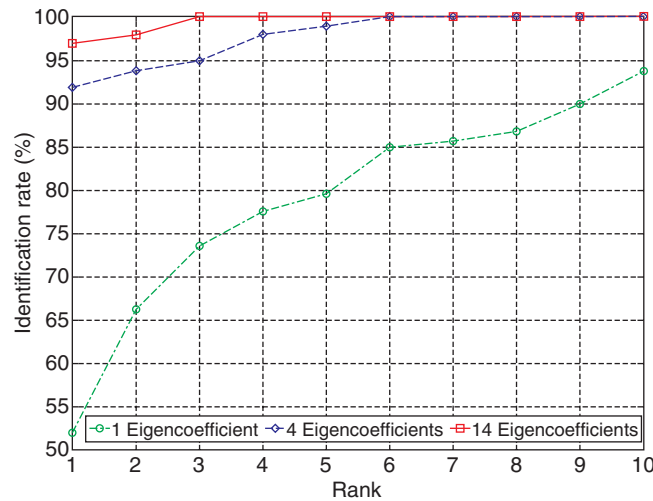


Figure 17.10 Cumulative match curve of the identification system: percentage of correct answers found in the top m best match, for several values of rank m .

THE IDENTIFICATION PROBLEM

The block diagram of the face verification system as seen in Figure 17.9 is still valid, with the difference that there is no claimed identity I_k , and the probe feature vector $\mathbf{v}_Q$ is matched against all templates $\mathbf{v}_i$ in the database.

The system can operate in two modes: *Watch list* – are you in my database?, and *basic identification* – you are in my database, can I find you? In both cases, the identification utilizes a *similarity* measure, S , which can be marked as true if it is above some threshold, t . In our experiment, we use the similarity between two feature vectors $S = 1/D_{WDTW}$. Table 17.2 shows a subset of the matching results: the rows correspond to the probes, which are matched against the gallery templates listed in the columns. The system is capable of recognizing the correct user since the similarity between utterances from the same subject is always greater than that between different subjects. In practice, the correct answer does not always correspond to the best match; therefore, the performance of the system is measured by plotting the cumulative match curve³⁴ as shown in Figure 17.10. The percentage of correct identifications found in the m best matches is calculated for several values of the rank m .

When the system is used in the *Watch list* mode, a threshold needs to be determined such that users who are unknown to the system are rejected (e.g., subjects O and P in Table 17.2). For example, threshold $t = 2.00$ can be a suitable choice.

PERMANENCE AND UNIQUENESS OF FACIAL ACTIONS

The discriminatory power of any biometric feature depends essentially on its permanence (i.e., the intrasubject variations should be small) and its uniqueness (i.e., the intersubject variations should be significant). Facial dynamic is a behavioral trait, and as such it is not expected to be strictly reproducible over time due to the variability of the subject's emotional and physical conditions. Our next experiment

Table 17.2 Similarity between data sequences $S = 1/D_{\text{WDTW}}$

Subjects	A	B	C	D	E	F	G	H	I	J	K	L	M	N
A	15.78	4.15	5.19	4.78	3.21	1.95	1.43	1.82	2.58	1.36	1.95	2.21	3.17	3.26
B	5.18	14.05	3.89	7.06	3.96	2.29	1.67	1.74	2.66	2.04	2.38	2.34	3.34	2.96
C	4.61	2.64	12.87	3.43	3.28	1.44	1.97	1.40	2.43	1.09	1.39	1.44	5.60	2.04
D	5.22	5.22	3.99	13.86	4.13	2.37	1.97	1.78	2.59	2.15	2.31	2.92	6.74	3.90
E	2.72	2.43	2.14	2.73	8.87	1.22	0.82	0.90	1.36	1.13	1.15	0.95	2.86	1.45
F	1.22	1.34	1.15	1.54	1.08	5.76	2.23	1.27	1.04	1.39	1.14	3.34	1.35	2.38
G	1.61	1.50	2.38	1.43	0.99	2.12	22.32	1.79	2.01	0.95	1.69	3.23	2.46	2.10
H	1.57	1.37	1.32	1.62	0.98	1.28	1.72	7.49	1.29	0.85	1.55	2.75	1.56	1.51
I	2.17	2.32	2.21	1.77	1.64	1.22	1.53	1.42	14.15	0.90	2.23	2.09	2.18	1.42
J	1.00	1.26	0.97	1.72	1.18	1.30	1.04	0.83	0.89	8.24	0.92	1.20	1.20	1.45
K	2.39	2.84	1.85	2.23	1.47	1.50	1.72	1.94	2.46	1.25	12.06	3.29	2.20	1.89
L	1.78	1.76	1.49	1.62	1.03	2.05	3.36	1.93	2.01	1.03	2.48	16.26	1.66	2.23
M	3.70	3.10	4.96	4.34	3.23	2.19	2.93	1.63	2.80	1.42	2.33	2.91	23.51	3.10
N	2.90	2.42	2.26	3.14	2.00	2.52	2.02	1.48	1.61	1.59	1.63	3.26	2.57	14.63
O	0.74	0.94	0.82	1.19	1.05	0.31	0.40	0.46	0.62	0.50	0.61	0.45	0.94	0.47
P	1.12	1.08	1.00	1.35	1.52	1.65	0.81	0.67	0.83	1.76	0.62	0.94	1.07	1.68

Columns, reference templates; rows, users "unknown" (to the system).

aims to measure to what extent facial dynamics can be considered permanent, and to assess whether the intersubject distinctiveness is sufficiently large compared with the intrasubject fluctuations.

Variations over long time intervals

Six different – H, J, V, C, G, and L – were recorded uttering the word “puppy” several times. All participants were natural English speakers with the exception of V. Recordings of H and G were taken over more than 2 years; I was recorded over 3 months, and D over 1 month. M was recorded on the same day, with only 15 minutes between the two recording sessions and with three repetitions per session. K was used as an unseen subject. The first utterances of five subjects, H1, J1, V1, C1, and G1, were employed to build a 3D ASM, which were then used to estimate the feature parameters of all the utterances. The pair-wise distances of the facial dynamics were computed and compared.¹⁵

Results show that the reproducibility of facial actions is very person-dependent. For example, the utterances of subjects H and G appear more stable over 2 years compared with those of V within the same day. Also, there is a greater similarity between utterances taken in the same session, for example {H1 and H2}, {H5 and H6}, {J1 and J2}, {J3 and J4}, {V1, V2, and V3}, {V4, V5, and V6}, etc. The distinctiveness across speakers is more significant than the intrasubject variations; thus, the clusters are accurately formed. L is an unseen subject who presents a very important dissimilarity to all of the subjects in the gallery. These observations indicate that facial dynamics of even very short facial actions provides sufficient discriminatory power to be used for person recognition.

Different speech postures

Figure 17.11 shows the dynamics of four different subjects uttering the word “puppy” several times. A careful examination shows that the closed syllable (short vowel) /pup/ appears more stable compared with the open syllable (long vowel) /-py/. In particular, the onsets of the syllable /pup/ are nearly identical. This observation holds for all the 94 subjects recorded in our database.

As shown in Figure 17.12, the repetitions of the word “password” (CVCC/CVC, long vowel/r-controlled vowel) seem to indicate that closed syllables are repeatable over time. This tendency can also be observed in the dynamics of other utterances. In other experiments, the closed syllables such as /diff/ in “cardiff,” /bub/ in “bubble,” and /bob/ appear reproducible across the repetitions, while the open syllables (long vowels) such as /-by/ in “baby,” and the two syllables in “mushroom” and in “ice cream,” present fluctuations in their dynamics, with regard to both the durations and the trends of the trajectories.²² The r-controlled vowel /car/ in “cardiff” and the l-e-controlled vowel in “bubble” also show significant fluctuations. These observations indicate that there is a hierarchy in the reproducibility of syllables, which means that some types of speech-related facial movement are more suitable for biometrics compared with others. However, our experiments are at an early stage and will need further investigation.

Nonverbal facial actions

Three sequences of the same subject performing a maximal smile are shown in Figure 17.13. The videos were captured over several months, and Figure 17.14 shows the temporal variations of the three lead Eigencefficients corresponding to the smile sequences. Considering the wide-ranging variety of smile patterns that a person can produce, we wish to standardize the performance and required the subject to perform an AU12 maximal smile (closed lips, no significant facial movements in other facial regions than the lips). Although clear instructions have been given, significant intrasubject variations and inaccuracies

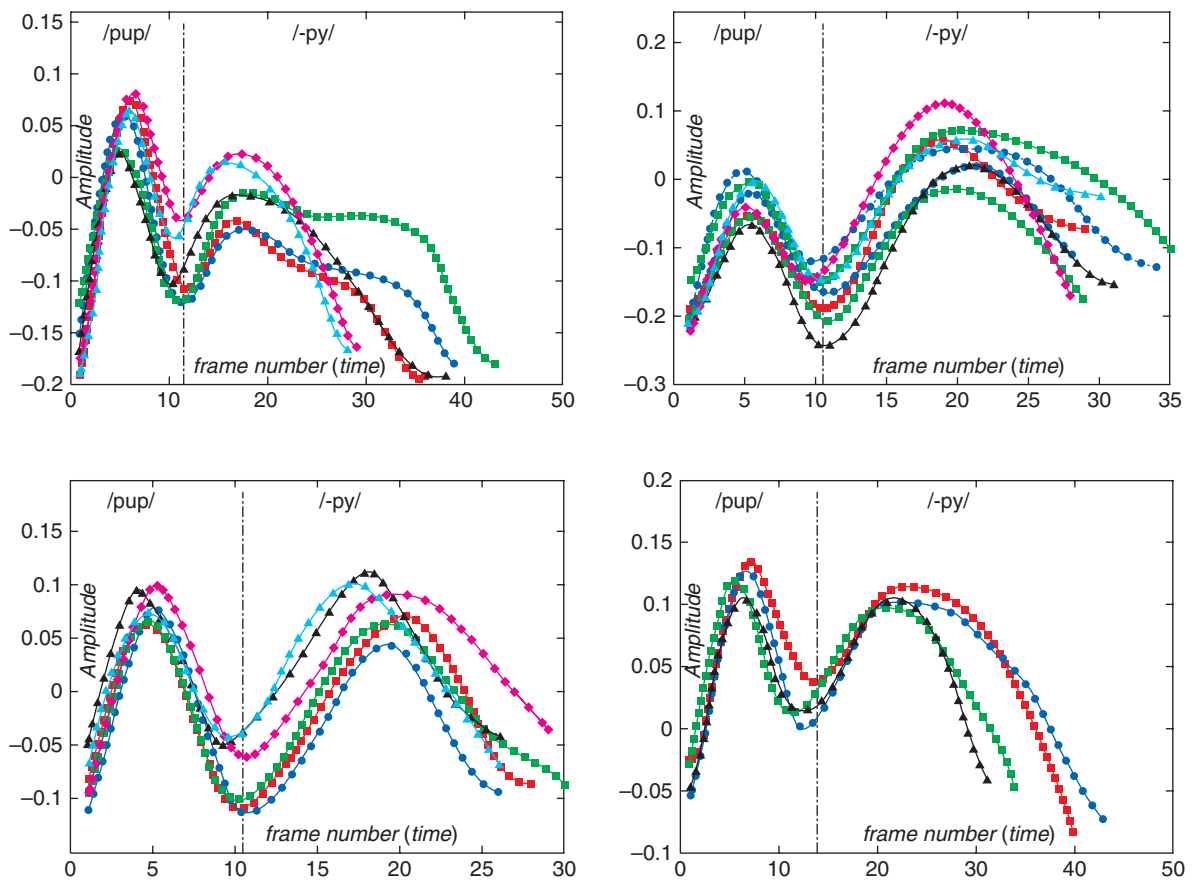


Figure 17.11 Reproducibility of the “puppy” utterances from four subjects recorded over several month intervals. Variations of the first Eigencoefficient are shown, which correspond to lip opening. The closed syllable /pup/ appears more stable compared with the open syllable /-py/. However, the coda of the /pup/ syllable seems to be affected by co-articulation.

can still be noticed across the repetitions, which result in the large fluctuations of the trajectories of the Eigencoefficients.

Examinations of the smile dynamics from 50 subjects show similar intrasubject variations and many occurrences of unwanted and nonrepeatable actions such as blinking, eyebrow movements, and facial asymmetries. For these reasons, the holistic feature extraction does not seem adequate. However, the local feature extraction approach also shows very poor recognition result because the lip motions alone are not sufficiently discriminative in the example of the smile. Other experiments have been carried out using the disgust expression, for which similar problems have been observed. For these reasons, we believe that nonverbal facial expressions are not suitable for biometric applications.

Finally, regarding the use of FACS AUs for person identification, we have observed during the recording sessions that it is very difficult for naïve users to produce accurate AUs, let alone to repeat identical performances. Figure 17.6 shows a subject performing AU9 (nose wrinkler). Perceptual evaluation

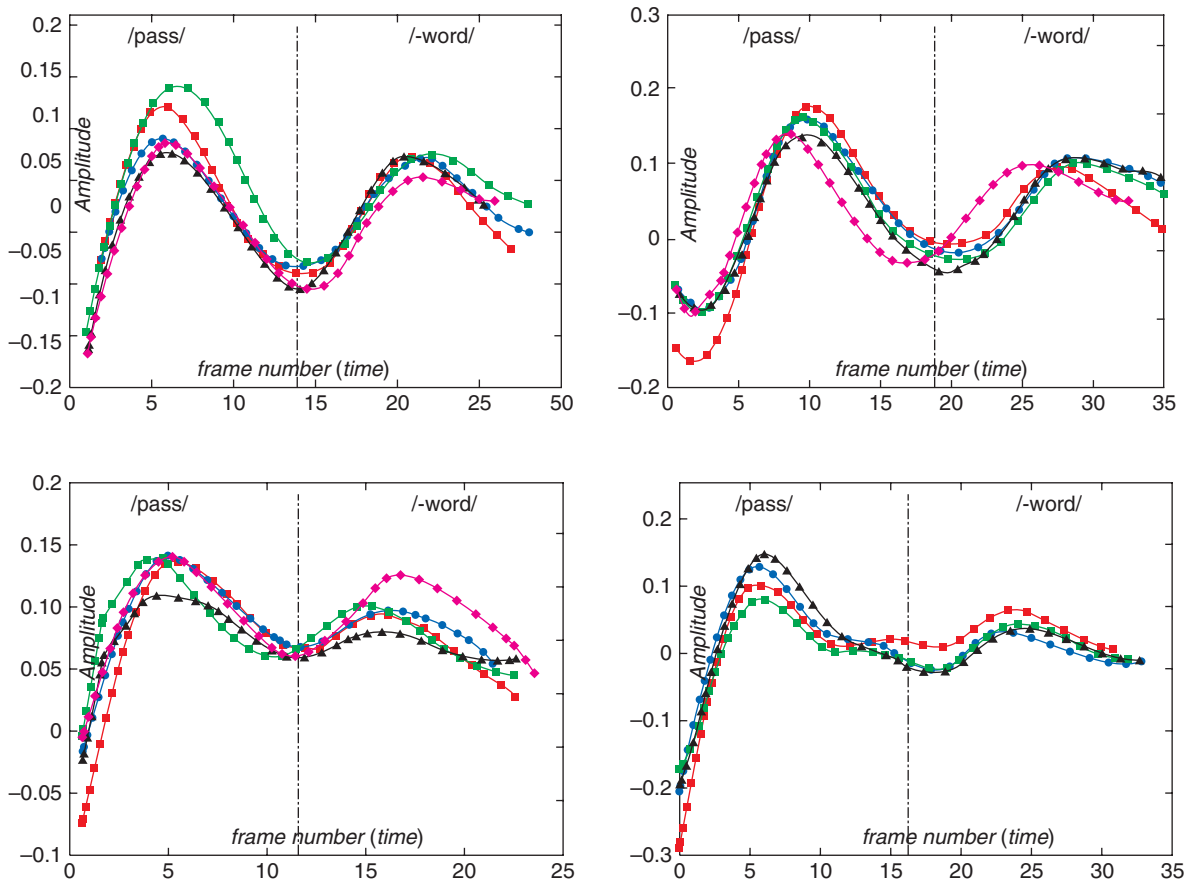


Figure 17.12 Dynamics of the “password” utterances of four subjects recorded over several month intervals. Variations of the first Eigencoefficient, which corresponds to lip opening.



Figure 17.13 Three video sequences of a naïve user performing an Action Unit 12-standardized maximal smile. The data were recorded over 3 months to assess the variability of the subject’s emotional and physical conditions. Significant variations and inaccuracies can be observed, for example lip opening, eyebrow movements, and facial asymmetries. The expression appears very unstable.

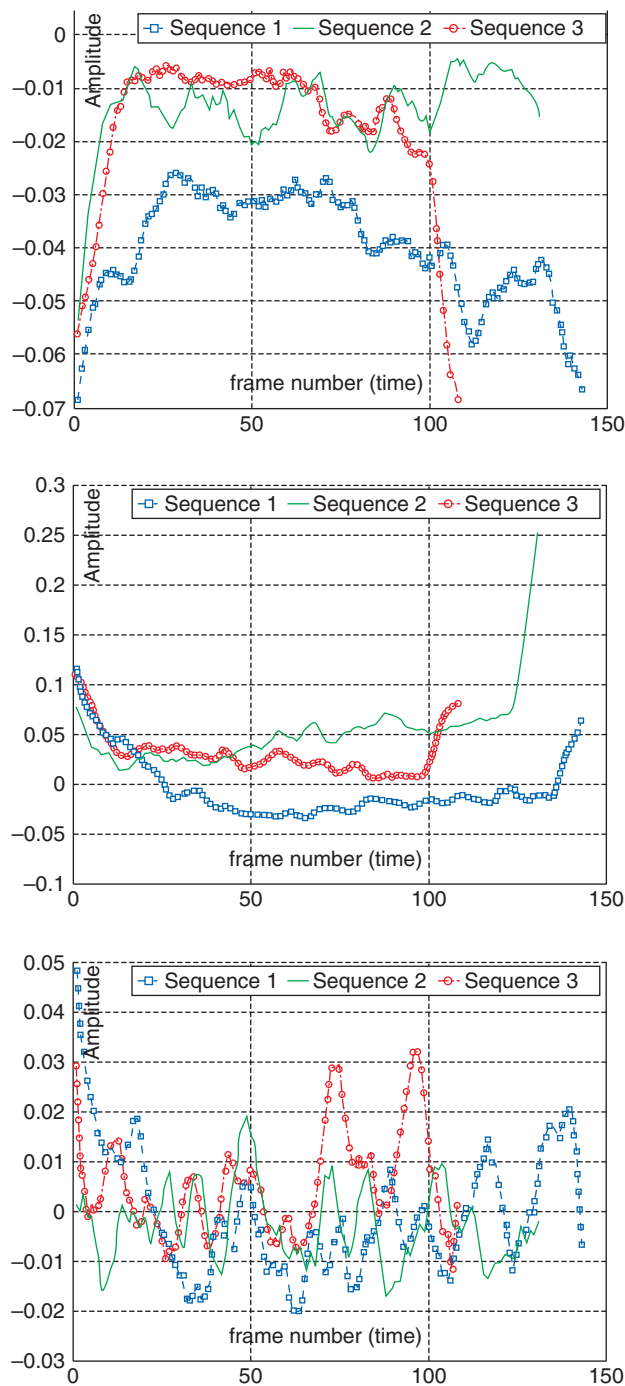


Figure 17.14 Smile dynamics corresponding to the three sequences shown in Figure 17.13. Variations of the three lead Eigencoefficients. In this experiment, we adopt the holistic feature extraction approach in order to capture the idiosyncrasies of the entire face.

undertaken by a FACS-trained psychologist has found this sequence to include not only AU9, but also other AUs. This raises the question of whether AU-based face expressions are suitable in a real-life scenario where users are not familiar with the FACS.

CONCLUSION

We have investigated the feasibility of using facial actions for biometric identification. Although previous work has been carried out on using lip motions for speaker recognition, there was very little emphasis on studying in depth the permanence and distinctiveness of facial motions. Furthermore, the problem has never been evaluated in an environment resembling a real-life scenario. We have reviewed the face databases and the recognition methods used in previous work, in light of which we have proposed several improvements.

First, we explain our choice of a new and meaningful set of *very short* verbal and nonverbal facial actions, which allow comparison of the biometric power of different types of facial movement. The evaluation is carried out on 3D dynamic data, which have been recorded over long time intervals to assess the variability of the subjects' emotional and physical conditions. The use of very short facial actions is essential in order to minimize the processing effort, which is very important for a real-time application such as face recognition.

A face recognition system has been implemented using facial dynamics and proposed an accurate pattern-matching algorithm derived from DTW. The results indicate that even *very short* verbal facial actions (e.g., the utterance of a two-syllable word) provide sufficient information for person identification. However, although speech-related facial motions show good potential, emotional expressions (e.g., smiling and disgust) and the FACS AUs appear very unstable, especially when naïve users are employed. This indicates that nonverbal expressions may not be suitable for biometrics.

In the particular case of speech-related facial motions, we observe that there exists a hierarchy in the reproducibility of different types of utterance. Whereas short vowels seem very repeatable, even over long time periods, long vowels show significant fluctuations. If we can establish formal rules to identify which types of facial motion are the most reproducible and discriminative across speakers, this will help users to select strong passwords, and the recognition performance will be improved.

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Please refer to the supporting companion website at: www.wiley.com/go/kau

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18

Nonrigid Image Registration Using Groupwise Methods

Kirill Sidorov, David Marshall, and Stephen Richmond

INTRODUCTION

Many medical tasks involve the analysis of a deformable object or a deformable structure within an object; examples include the study of variation, classification, atlas look-up, anomaly detection, and segmentation (the partitioning of a digital image into two or more regions). Tasks like these are often performed by specialists (e.g., radiologists) who rely on binocular vision and human judgment to convert raw data into a clinically useful form. This is often a subjective, error-prone and time-consuming process. Recent advances in machine vision make it possible to automate some of the image analysis and interpretation tasks. Automatically establishing dense correspondences between samples of a deformable object (Figure 18.1), otherwise known as nonrigid registration in the literature, has attracted significant interest in the research area of medical image analysis.¹

In this chapter, we will focus on the nonrigid registration as it is one of the most fundamental problems in computer vision and also has importance in a wide range of clinical applications. Given a set of samples of a deformable object, it is only when correspondences between the samples are established that any form of meaningful analysis of the whole set can be performed.

REGISTRATION

First, we will consider an important special case of the registration problem – establishing correspondences between elements of a set of images (e.g., photographs, radiographs, depth maps measured by range scanners, computed tomography slices, or magnetic resonance imaging volumetric data).

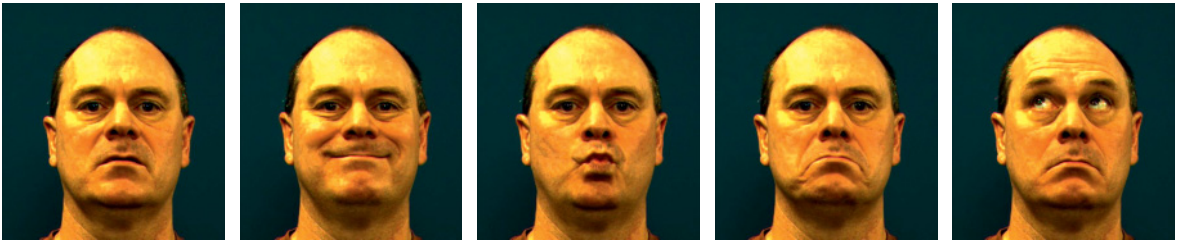


Figure 18.1 Anatomic structures can undergo highly nonrigid deformations.

Applications of image registration methods are vast, so it is unlikely that generic methods can be developed that are fit for purpose for a wide range of applications.

Rigid versus nonrigid transformations

By convention, image registration methods are often classified according to their transformation model into “rigid” (translation, rotation, and scaling) and “nonrigid” (complex deformations). Rigid methods aim to find the optimal affine transformations of the images, with respect to a common coordinate frame, that bring the images into correspondence. In other words, these methods assume only a global (entire image) deformation model. Nonrigid methods operate under a less restrictive assumption, and the images are allowed to undergo more general and complex deformations, including local (subsections of the image) warping. This is often the case with medical imaging due to the complex mechanical deformations within and between subjects.

Nonrigid methods are further subclassified according to their transformation model. The most common type of nonrigid transformation models are piecewise linear, spline-based and fluid-based.^{2–5} Transformations between images need not be spatial. For example, Learned-Miller considered a problem of groupwise registration (in his paper termed “congealing”) but applied this to the optimization of spatial and also nonspatial modes of deformation (e.g., brightness).⁶

Groupwise versus pairwise

There is an important distinction between registering a *pair* and a (large) *set* of images. One might naïvely assume that, given an algorithm to establish correspondence between a *pair* of images, correspondences between *multiple* images could be found by the repeated application of such a pairwise algorithm. An example of such a naïve approach would be to select one of the images from the set as a reference and then repeatedly register all other images to this reference. However, this approach frequently used in the past may be *fundamentally* flawed because, at any given time, not all the available information is used, only the information from a pair of images. A survey of pairwise registration methods is found elsewhere.⁷

Repeated application of a pairwise registration algorithm will inevitably be biased to the choice of reference image, which leads to errors in the final alignment.⁸ In addition, an unfortunate choice of reference, for example if it has missing features or is not representative of the entire set, will degrade the performance of the algorithm further. To combat such issues, recently developed groupwise approaches that consider and bring an entire group of images into registration simultaneously endeavor to use all

the available information from all images in the set.^{2,3,8} Here, the information from the *entire* dataset is being utilized at each stage, rather than that from only a pair.

Only from multiple images can the features that are reliable enough to be registered be discriminated from those features that are unimportant (structures that are only transient, or noise) and should be ignored. Early experiments with the groupwise approaches were concerned with finding dense correspondence across a set of unlabeled images and have been shown to be superior compared with pairwise methods.³ Despite established superiority, it was not until recently that the practical implementations of groupwise methods were considered. The reason for this is the extra cost (computational effort) with which the superior quality of the groupwise registration comes.

PROBLEM DECOMPOSITION

Image registration may be broken down into three subproblems:⁹

- A mechanism for representing and manipulating dense correspondence between images. This is the model of transformations that the images undergo.
- An objective function, F , measuring the quality of registration given the dense correspondences between samples (i.e., a particular instance of the transformations), with a minimum at a point corresponding to the desired registration.
- A global minimization algorithm that optimizes F over the space of all possible parameters describing correspondence between images.

Global minimization of the objective function, F , whose arguments are correspondences between all images and whose value measures the quality of registration, solves the problem. However, unlike with pairwise methods, when correspondences between multiple images are considered, the dimensionality of the space in which the search for the optimal solution is performed grows very rapidly with the number of samples in the set when the groupwise approach is employed. In practical problems, very high dimensionality of the search space presents a significant obstacle to finding the optimal solution.¹⁰ Suppose N images are to be registered, and the correspondences between images are controlled by K degrees of freedom per image, yielding $2NK$ degrees of freedom in total; even for a modest dataset (hundreds of images) and a modest resolution of deformations (tens of degrees of freedom per image), the dimensionality of the space in which the solution is to be found is measured in thousands.

The problem of efficient optimization of the very high-dimensional objective function in the context of groupwise image registration has not been explored extensively in the literature. Most traditional optimization algorithms used in previous studies cannot deal with an optimization problem of such magnitude and tend to converge to local minima.^{2,3} Some stochastic algorithms (e.g., simulated annealing and genetic algorithms), which attempt to avoid local minima, have impractical computation times even for small datasets. The main contribution of this chapter is to describe an efficient optimization framework for many-dimensional groupwise objective functions for nonrigid image registration that can quickly and reliably find the best minima.

Our approach alleviates the “curse of dimensionality” by offering:

- a novel solution that implicitly reduces the dimensionality of the search space as the search progresses by incrementally learning optimal deformations;
- a novel application of stochastic optimization algorithms that do not significantly degrade in performance as the dimensionality grows.

In addition, due to the efficient formulation, it is amenable for graphic processing unit (GPU) implementation – apart from the control logic, all steps can be performed on a GPU.

Due to the robustness of our method, we are also able to perform *interperson* groupwise registration: we take a corpus of individual face images and can successfully register them.¹¹ This is the first time that the automatic nonrigid registration of data possessing such variety has been reported.

Problem statement: groupwise registration

The input to the registration algorithm is a (possibly unordered) set of N images $\{I_i, i = 1 \dots N\}$ of different examples of a deformable object or a deformable structure in an object. We seek to automatically (without user intervention) derive a dense spatial correspondence between the examples. Deformation fields (one for each image) define spatial correspondences between the images, by specifying where each pixel on the underlying object structure is located on that image.

Groupwise registration algorithm

The algorithm is briefly outlined below (full details having been published elsewhere).¹² Groupwise registration can be considered as an optimization problem. Prior to explaining the optimization regime, the deformation mechanism and the objective function to minimize will be defined first.

Deformation mechanism

The most common ways to represent deformation fields that transform one image into another are fields defined by a sparse set of control points that control either a set of splines,⁵ the nodes of a triangulated mesh,³ or compositions of simple warps,² or dense fields representing the displacement of each pixel.⁴ The proposed approach uses both dense deformation fields (to store accumulated deformations) and fields controlled by sparse sets of points (when incrementally improving accumulated deformations). In the latter case, for computational efficiency, we piecewise linearly interpolate the deformation inside the triangles of a mesh obtained by triangulating the set of control points, given the deformations at vertices (control points).³ Although this representation has been previously criticized for being insufficiently smooth,² and has limited flexibility and spatial resolution,¹³ this is no longer a problem with the proposed method, which benefits from its computational efficiency without any sacrifices.

Let $\mathbf{D}$ denote a dense deformation field; we store a deformation field in a vector-valued matrix (deformation map, of the same size as the images) whose elements contain the pixel displacements. Thus, given an image I and a dense deformation map $\mathbf{D}$, a warped image I' is obtained thus: $I'(\mathbf{x}) = I(\mathbf{x} + \mathbf{D}(\mathbf{x}))$, $\forall \mathbf{x}$, which we will abbreviate to $I'(\mathbf{x}) = W(I, \mathbf{D})$; this is illustrated in Figures 18.2, and 18.12, below. Given two (ordered) sets of control points C_1 and C_2 placed correspondingly in images I_1 and I_2 , a dense deformation map from I_1 to I_2 can be obtained by interpolation as described above; we will abbreviate it thusly: $\mathbf{D} = L(C_1, C_2)$.

Incrementally learning optimal deformation

Let there exist a dense set of control points, C_D , and a sparse subset of C_D , $C_S \in C_D$. Suppose, for ease of explanation, that they are vertices of a triangular mesh describing the deformation of an image (in Figure 18.3a, C_D is all points, and C_S is points on the solid lines). Let C_{D-S} denote the set of points in C_D not in C_S (in Figure 18.3a, solely on dashed lines). If we could express the optimal position of points in C_{D-S} as

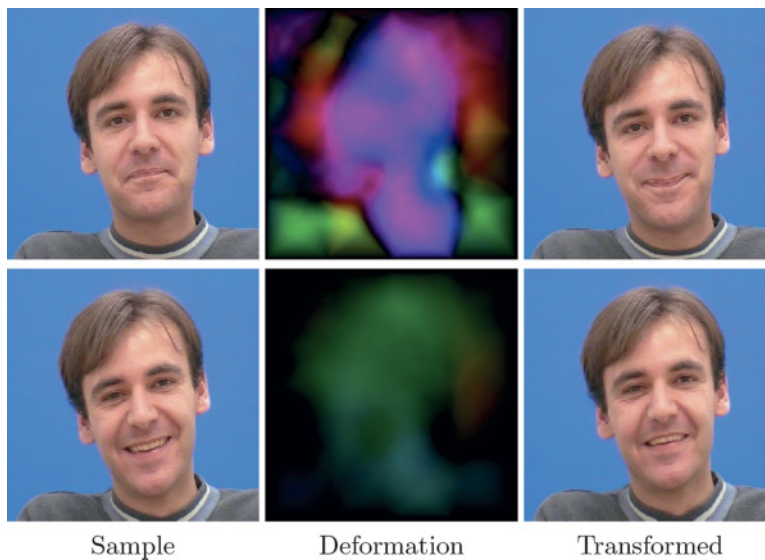


Figure 18.2 Samples from the FGnet dataset together with the computed deformation maps and shape-normalized images. In deformation maps, color indicates direction, and brightness indicates the magnitude of the displacement. (Frank Wallhoff: Facial Expressions and Emotion Database <http://www.mmk.ei.tum.de/~waf/fgnet/feedtum.html>, Technische Universität München 2006.)

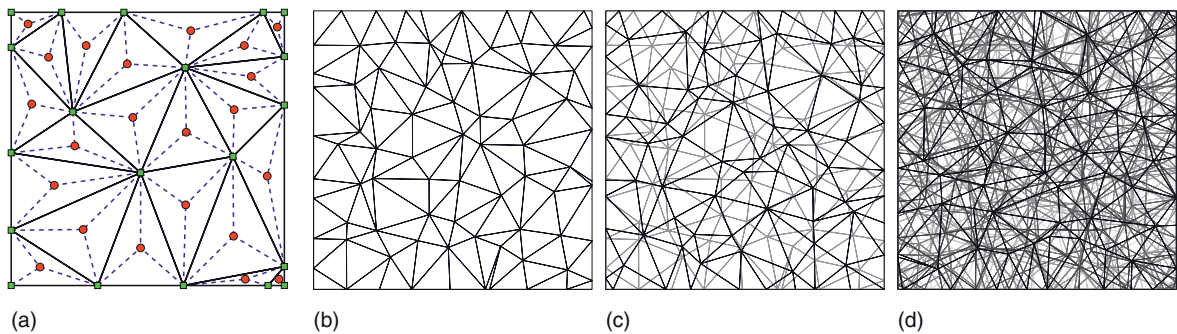


Figure 18.3 Superposition of random meshes. (a) A dense mesh and its subset. (b) One mesh. (c) Two meshes. (d) Eight meshes. C_D , dense set of control points; C_S , sparse subset of C_D .

a function of optimal position of points in C_S , this would obviously yield a dimensionality-reducing reparameterization of the deformation; by means of this, we would be able to control more complex deformations with the same number of control points (increased resolution) or control the deformations with a smaller number of control points keeping the same resolution (dimensionality reduction).

Unfortunately, such a function is not known in advance. Instead, we propose to incrementally learn and accumulate the optimal dense deformation everywhere *between* the sparse control points. The *power* of our algorithm comes from this fact. We use control points only when searching for an optimal improve-

ment for an already established *dense* deformation map. Moreover, instead of using only one set of control points, as other approaches do, we randomly generate a completely new set of control points at each minimization stage. This allows us to approximate more and more complex deformation fields as a superposition of simple deformation fields (parameterized by control points at each stage), as the algorithm progresses. As we use a new random mesh each time, we progressively sample points on the underlying accumulated deformation field with increasing resolution (Figure 18.3b–d).

It is critical to note that when a new set of control points is generated, the improvements obtained using the previous set are not lost but are accumulated into dense deformation maps. Also note that the number of control points (and thus the number of optimization parameters) always remains the same. The key to the power stems therefore from the ability of our algorithm to search for more and more complex deformations while keeping the dimensionality of the search space constantly low.

Objective function

Let $G(I_i, I_j)$ be the pixelwise discrepancy function for images I_i and I_j (of size $r \times c$):

$$G(I_i, I_j) = \frac{1}{rc} \sum_{\mathbf{x}} g(I_i(\mathbf{x}), I_j(\mathbf{x})), \quad (1)$$

where $g(a, b)$ is a pixel discrepancy function that can be simply $g(a, b) = |a - b|$ or $g(a, b) = (a - b)^2 / (1 + (a - b)^2 / d^2)$ (Geman–McClure function). Also, let D_i^a denote the corresponding deformation map for an image I_i . We then define the groupwise objective function, F , as follows:

$$F(D_1^a, \dots, D_N^a) = \frac{1}{N} \sum_{i=1}^N G \left(W(I_i, D_i^a), \frac{1}{N-1} \sum_{j \neq i} W(I_j, D_j^a) \right) \quad (2)$$

This amounts to computing the average discrepancy between every image warped to the reference space and the current estimate of the reference computed by averaging all other shape-normalized images.

From the information-theoretical point of view, an attractive choice for the objective function is the so-called minimal description length (MDL) of the model (set of transformed images).^{8,5} For implementation on a GPU, however, our discrepancy-based cost function is more suitable. However, the MDL could be substituted with no loss of generality.

Optimization regime

A naïve attempt to minimize F in Equation (1) would be to exhaustively search in the space of all possible deformation maps, D_i^a , for all N images. In practice, some reparameterization of D_i^a is used, for example using control points defining triangular meshes³ or splines.⁵ Even after such reparameterization, finding a minimum of our objective function is a difficult task since the number of parameters in the optimization is still very large.

It has been shown that it is sufficient to optimize the deformations of one image at a time.^{3,10,14} This is equivalent to optimizing a $2NK$ dimensional objective function along $2K$ dimensions at a time and is analogous to Powell’s classic optimization method. In our method, we adopt a similar technique: as we show below, in an iterative fashion, for one image at a time, we improve its corresponding deformation map, which leads to a minimization of Equation (2).

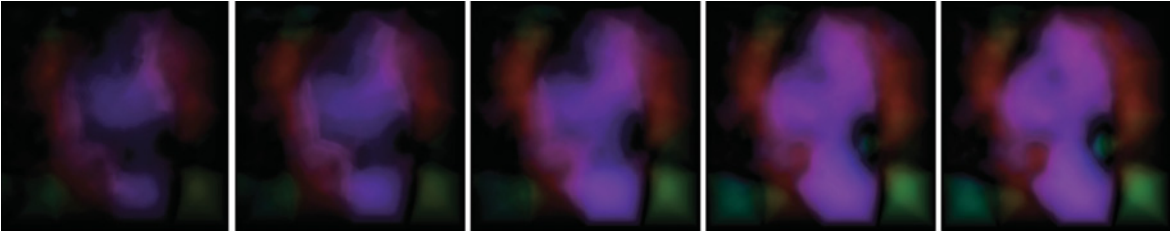


Figure 18.4 Evolution of the deformation map for one image as the algorithm progresses.

We now give an overview of the registration procedure; full details have been published elsewhere.¹²

- First, the deformation maps $\mathbf{D}_{i_0}^a$ for all images are initialized to identity transform.
- The algorithm then operates by incrementally improving the accumulated deformation maps, $\mathbf{D}_{i_k}^a$, in an iterative fashion. This iterative body is repeated until no further improvement is possible.
 - In order to avoid biasing the algorithm, we randomize the order in which the images in the set (and their corresponding deformation maps) are processed: at each iteration we randomly permute the set.
 - When optimizing deformations for each image I_i , first compute an estimate of the reference image M_{ik} by averaging all images I_j (except I_i) transformed to the reference space using the deformation learnt at the previous stages $\mathbf{D}_{j_{k-1}}^a$ and the improvement $\Delta\mathbf{D}_{jk}$ learnt at the current step.
 - The optimal improvement $\Delta\mathbf{D}_{ik}$ is then computed (using a procedure outlined below) by minimizing $G(M_{ik}, W(I_i, \mathbf{D}_{i_{k-1}}^a + \Delta\mathbf{D}))$ over the space of all possible improvements $\Delta\mathbf{D}$.
 - After the deformations of all images have been improved, the improvements are added to the previously learnt deformations and the process repeats. The evolution of the deformation map for an image is illustrated in Figure 18.4.

We next address the outstanding problem of minimizing $G(M_{ik}, W(I_i, \mathbf{D}_{i_{k-1}}^a + \Delta\mathbf{D}))$ as a function of $\Delta\mathbf{D}$ that is exacerbated by its nonlinear nature and many local minima.

Stochastic optimization

Most traditional deterministic optimization algorithms, such as Downhill Simplex² and gradient descent,³ cannot efficiently deal with an optimization problem of the above magnitude and tend to converge to local minima, especially in the presence of measurement noise.¹⁰ Some stochastic algorithms, such as simulated annealing and genetic algorithms, have been designed to avoid local minima. However, such techniques tend to be inefficient and have impractical computation times even for small datasets. Thus, one of the most challenging aspects in the development of optimization approaches to groupwise registration is designing an efficient minimization routine.¹⁰

Simultaneous perturbation stochastic approximation (SPSA) is an attractive choice for the optimizer. It is capable of evading local minima due to its stochastic nature and, when adapted for our framework, is orders of magnitude more efficient¹⁵ than the traditional stochastic algorithms. Moreover, whereas in traditional gradient-based methods the number of function evaluations required to estimate the gradient at a point grows linearly with the dimensionality of the space, SPSA offers independence of the number

of function evaluations at each iteration on the dimensionality of the space. An overview of the SPSA algorithm can be found elsewhere,¹⁶ but for completeness we will outline the algorithm here.

Let $f(\phi)$ be a real-valued function and ϕ be a p -dimensional vector of parameters. Assume that only the direct measurements of $f(\phi)$, but not of its gradient, are available. Measurements of $f(\phi)$ might also be noisy, and p might be very large. We aim to minimize $f(\phi)$ to find $\phi_{opt} = \operatorname{argmin} f(\phi)$. Let $\delta = (\delta_1, \delta_2, \dots, \delta_p)^T$ be a vector of independent random variables with symmetric Bernoulli distribution: $\delta_i = \pm 1$ and $\Pr(\delta_i = 1) = \Pr(\delta_i = -1) = 1/2$. Let $\hat{g}(\phi)$ denote the stochastic approximation of the gradient $g(\phi)$:

$$\hat{g}(f(\cdot), \phi, c_k, \delta_k) = \begin{pmatrix} \frac{f(\hat{\phi}_k + c_k \delta_k) - f(\hat{\phi}_k - c_k \delta_k)}{2c_k \delta_{k1}} \\ \vdots \\ \frac{f(\hat{\phi}_k + c_k \delta_k) - f(\hat{\phi}_k - c_k \delta_k)}{2c_k \delta_{kp}} \end{pmatrix} \quad (3)$$

and ϕ denote the “current” estimate for ϕ_{opt} .

The SPSA algorithm incrementally updates ϕ_{opt} by the following process:

$$\hat{\phi}_{k+1} = \hat{\phi}_k - a_k \hat{g}(\hat{\phi}_k) \quad (4)$$

The gain sequences c_k and a_k are chosen as follows: $a_k = \frac{a_0}{(A+k)^a}$ and $c_k = \frac{c_0}{k^\gamma}$. Note that at each iteration, k , only *two* $= O(1)$ evaluations of f are required, as opposed to $O(p)$ in traditional gradient-based methods. Extensive convergence theory¹⁷ establishes performance guarantees for SPSA and shows that $\hat{\phi}_k \rightarrow \operatorname{argmin} f(\phi)$ as $k \rightarrow \infty$.

As stochastic algorithms are notoriously hard to tune, we now address the issue of tuning the SPSA. The tuning parameters c_0 and a_0 are measured in units of image size (say, pixels) and control the “greediness” of the algorithm – larger values correspond to a less greedy search. We choose c_0 to be about 1–4% of the image size, and experimentally choose a_0 to be of the same order of magnitude. The decay parameters α and γ are set to the theoretically optimal values $\alpha = 0.602$ and $\gamma = 0.101$, see Spall’s original paper¹⁸ which also covers the choice of tuning parameters in various settings.

REGISTRATION EXPERIMENTS

We used a subset of 128 images from the publicly available Face and Gesture Recognition Work Group FGnet “talking face” dataset.¹⁹ For the interperson registration experiment, we used the frontal images²⁰ from the publicly available Informatics and Mathematical Modelling (IMM) face database.¹¹ We have also applied our algorithm to brain and face datasets acquired in our laboratory, with similar results.

As the algorithm progresses and incrementally establishes the correct correspondences, the shape-normalized average of the images converges to a true, crisp picture of the underlying structure (Figure 18.5). This means that all images have been well aligned by the groupwise registration. With interperson data, the average of nonshape normalized (no registration) images does not exhibit much structure, but after applying our algorithm we get a good approximation of the average face (Figure 18.6). There is considerable variation in the interperson dataset, but the algorithm admirably copes with this.

The SPSA proves to be very suitable for global optimization.¹⁷ The comparison of our approach with incremental learning of the deformations with the traditional approaches that do not do this is highlighted



Figure 18.5 Evolution of the mean shape-normalized face. Shown after $n = 0$, $n = 32$, $n = 64$, and $n = 128$ iterations of our algorithm. (Frank Wallhoff: Facial Expressions and Emotion Database <http://www.mmk.ei.tum.de/~waf/fgnet/feedtum.html>, Technische Universität München 2006.)

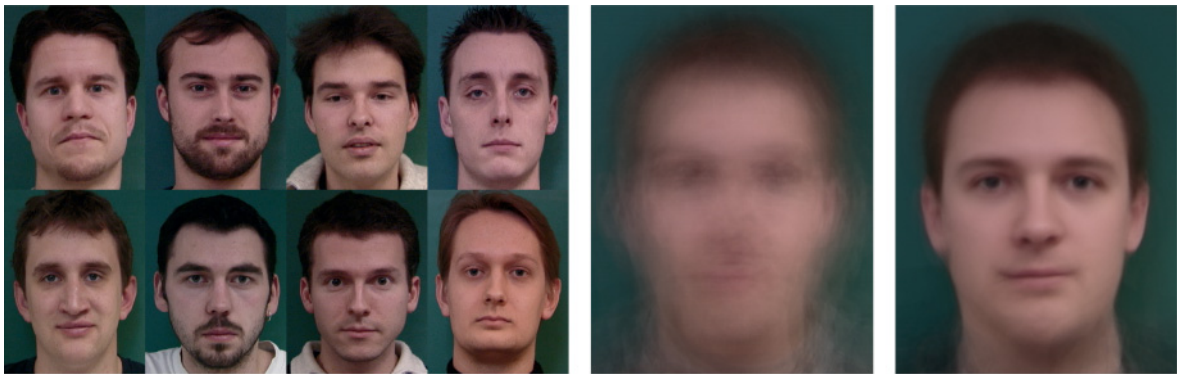


Figure 18.6 Interpersonal registration. Left: Data from the samples. Middle: Averaged images (no registration). Right: Averaged shape-normalized images after registration with our algorithm. (From Nordstrøm MM, Larsen M, Sierakowski J, Stegmann MB, 2004.¹¹ See also <http://www2.imm.dtu.dk/~aam/>)

(Figure 18.7). To evaluate the performance, the objective function at each iteration was evaluated. The SPSA was used as the optimizer in each case. The FGnet dataset was used.¹⁹

As shown in Figure 18.7, our approach yields an improvement in the speed of convergence and converges to better minima. It is also important to note that our method requires no initialization (although conventional approaches benefit from initialization).³ The FGnet dataset contains a lot of affine deformations (head movement); it helps to initialize the algorithm by performing rigid registration first (dashed lines). In our experiments, after such initialization the algorithm more quickly arrives at the solution, but at the cost of a minor loss in accuracy: this initialization is essentially too greedy a search and tends to throw the algorithm into strong but not necessarily the best local minima. All approaches appear better than a hand-labeled annotation of the data.

In all experiments, the algorithm numerically demonstrates linear convergence. Note, however, that the critical performance cost is the number of objective function evaluations and not the number of iterations. This is an important property and compares favorably with other optimizers. Comparing the SPSA

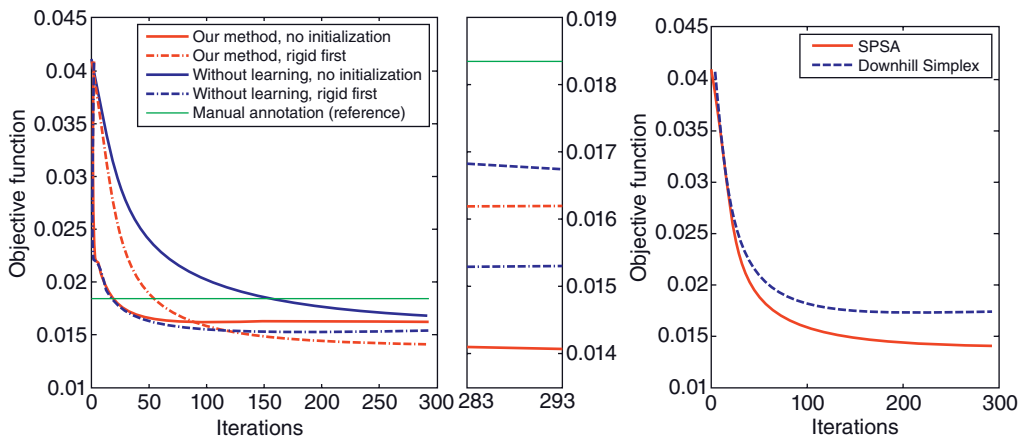


Figure 18.7 Comparison of algorithm performance. (Left) With and without incrementally learning the deformations. (Center) Rightmost part of the trace magnified. (Right) Simultaneous perturbation stochastic approximation versus the Downhill Simplex method.



Figure 18.8 An Active Appearance Model of a talking head. (Left) -2 standard deviations (SD). (Center) Mean. (Right) $+2$ SD. (Frank Wallhoff: Facial Expressions and Emotion Database <http://www.mmk.ei.tum.de/~waf/fgnet/feedtum.html>, Technische Universität München 2006.)

with the commonly used Downhill Simplex method, better optimal solution and convergence rate were achieved (Figure 18.7, right).

Having registered the images, statistical appearance models can be constructed, using deformation maps directly to build a high-resolution shape model. If memory is a concern, one might obtain a traditional control point-based representation of shape in the end by sampling the deformation maps. The first two modes of variation of combined model of the FGnet dataset are shown in Figure 18.8.

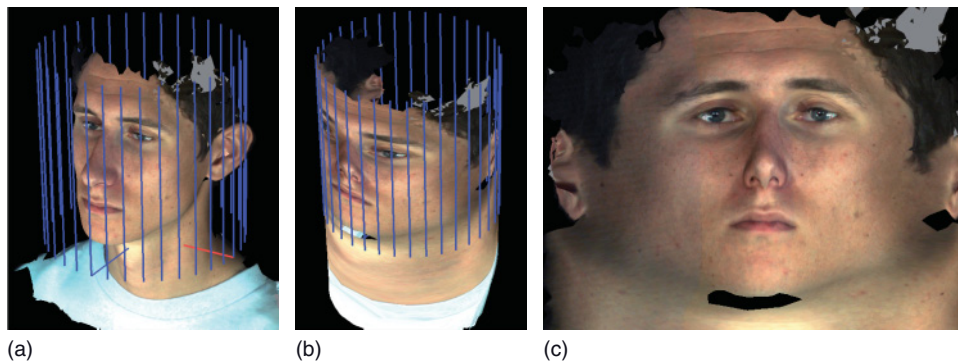


Figure 18.9 Mapping a surface onto a rectangle: (a) original surface; (b) surface projected onto a cylinder; and (c) the cylinder unwrapped.

REGISTERING SURFACES

This method can be generalized and applied to the registration of texturized three-dimensional (3D) surfaces such as those produced by 3D cameras (see Figure 18.9a). The advantages of the approach outlined below are twofold. First, we argue that if the textural information is available, it should be used (potentially, in conjunction with the shape information) when registering surfaces, rather than using shape alone. This is due to the fact that textures contain useful information that can facilitate registration. We hypothesize that, in practice, the information content of the textures is often much higher than that of the underlying surfaces (meshes). Second, we present a reduction of the surface registration problem to the already described case of two-dimensional (2D) image registration, thus preserving all the advantages of our method.

Below, we assume that surfaces are approximated with a triangulated mesh and the textures are available, together with the corresponding texture coordinates. Given the topologic equivalence of the surfaces in question to a disk, the idea is to map the surfaces onto a rectangle, remembering the mapping and warping of the corresponding textures accordingly. The above registration algorithm can then be used to bring the samples into correspondence by registering their textures; after they have been registered, the inverse mapping from the rectangular domain back to the original space can be performed on the registered samples to reconstruct corresponding shapes in 3D space.

One way to accomplish this is to project the mesh onto a side surface of a cylinder and then unwrap the side surface into a rectangle, subjecting the latter to our algorithm. The original surface approximated by a triangular mesh is shown together with the cylinder outline (Figure 18.9a), the projection onto the cylinder (b), and the unwrapped cylinder (c). The cylindrical unwrapping is sufficient for our purposes, although a potentially better approach is presented elsewhere.²¹

When thus mapping the surfaces, in addition to the texture map, we also generate a *shape map*, of the same size as the texture map, which stores the original 3D coordinates of the points in the texture map. In other words, for every texel (texture pixel) in the texture map, we know the true 3D coordinates. A visualization of such a shape map is presented in Figure 18.10a.

The registration is then performed on the texture maps, and the optimal deformation maps (Figure 18.10b), bringing the images into correspondence, are obtained. These deformation maps tell us not only how the textures should be deformed, but also how the corresponding shape maps (and therefore the

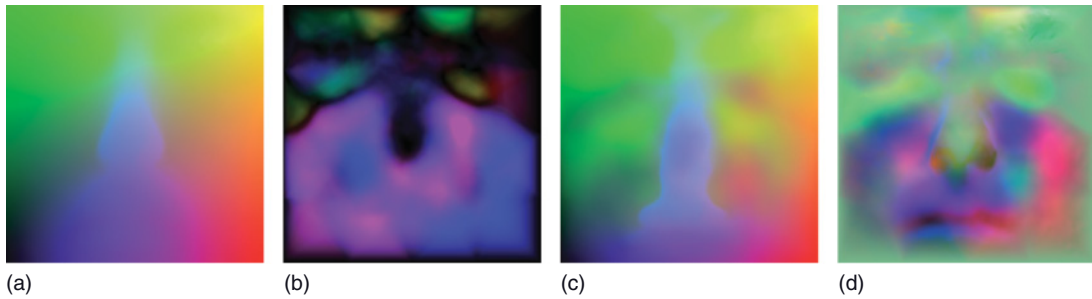


Figure 18.10 Applying deformations to the shape maps. The shape maps are color-coded, with the red, green, and blue components corresponding to the x -, y -, and z -coordinates. (a) A shape map. (b) A deformation map computed by the registration algorithm. (c) The result of applying the deformation map. (d) The difference between the original and the deformed shape maps (magnified).⁹



Figure 18.11 Registration example. (Left) Data from the samples. (Center) Averaged images (no registration). (Right) Averaged shape-normalized images after registration with our algorithm.

equivalent surfaces) should be deformed (due to one-to-one mapping between the texture maps and the surfaces).

By applying the deformation maps to the shape maps, we obtain new shape maps that can then be converted back to the original 3D mesh form. The shape maps can therefore be manipulated in 2D, and thus so too can their corresponding surfaces. This is illustrated in Figure 18.10.

For clarification, we will register a sequence of surfaces from Figure 18.9. After having unwrapped the texture maps and generated the shape maps, we subject the texture maps to our registration algorithm. Figure 18.11 summarizes the registration results: on the left samples from the original data are shown (texture maps; here, cropped around the region of interest for compactness); in the middle and on the right are shown the shape-normalized averages of all textures before and after registration, respectively. Registration produces the optimal deformation maps, which, being applied to the textures, bring them into correspondence. Figure 18.12 compares the original texture (a) to which a deformation map (b) is applied, with the deformed texture (c) and the shape-normalized average of all textures in the set after registration (d). Deformation maps are then applied to shape

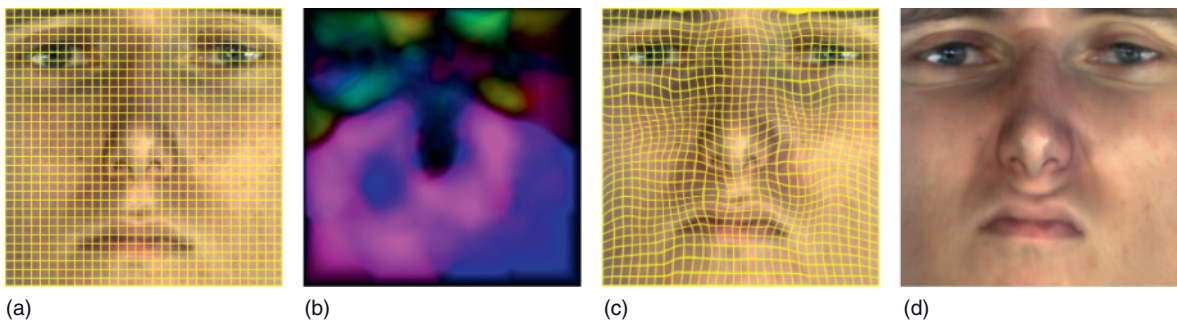


Figure 18.12 Applying deformations to the texture maps. (a) A texture map. (b) A deformation map computed by the registration algorithm. (c) The result of applying the deformation map to the texture map. (d) The average of the shape-normalized textures.

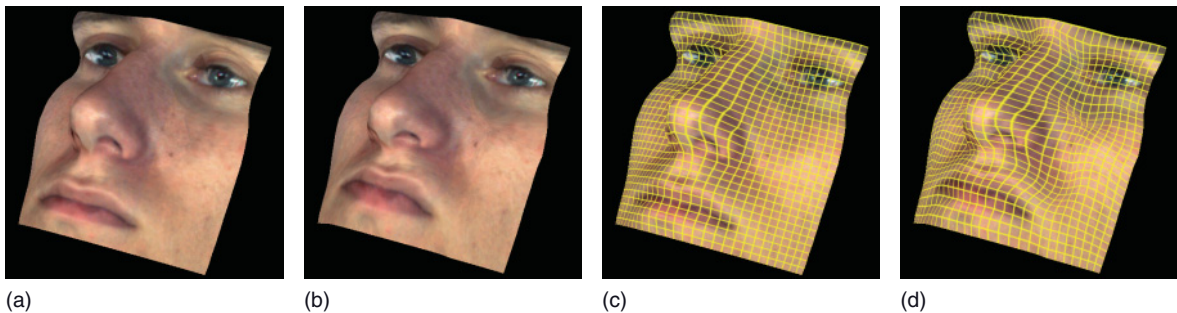


Figure 18.13 Reconstruction of the three-dimensional view from shape maps. (a) The surface reconstructed from the shape map in Figure 18.10a. (b) The surface reconstructed from the shape map in Figure 18.10c (deformed). (c) The same as Figure 18.13a with a grid. (d) The same as Figure 18.13b with a grid.

maps (Figure 18.12). Finally, the results of the inverse mapping from shape maps to 3D surfaces are shown (Figure 18.13).

CONCLUSION

A novel approach to groupwise nonrigid image registration that requires no initialization has been described. We have developed methods that implicitly reduce the dimensionality of the search space by representing increasingly complex deformations as a superposition of simpler deformations. Due to this formulation, we are able to take advantage of the simplicity and speed of piecewise linear interpolation to model deformations and overcome previous limitations of this approach due to limited smoothness, flexibility, and spatial resolution. We also use a novel efficient and reliable, fully unsupervised stochastic optimizer (an adaptation of SPSA), which is independent of the number of function evaluations at each iteration on the dimensionality of the space.

In the evaluation of our method, we have demonstrated a high robustness and success rate, fast (linear) convergence on various types of test data, which shows considerable improvement in terms of accuracy of solution and speed compared with existing methods. Due to the robustness of our approach, we are also able to perform *interperson* registration.

Please refer to the supporting companion website at: www.wiley.com/go/kau

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19

Three-Dimensional Developments for the Future

Stephen Richmond and Chung How Kau

THE PAST

Three-dimensional (3D) measurements have been possible since the concept of what we know as Pythagoras' theorem, documented around 500 BC, although it is known that the Babylonians were aware of the concepts 1000 years previously. Perhaps it was Pythagoras that proved the theory and became a "household" name. As basic trigonometry can be used to define and quantify shapes and volumes, it has been used by surveyors, architects, and designers to create objects and buildings. It is easy to construct objects from plans, but it has been harder to achieve the reverse, that is, to develop 3D plans from established structures.

In 1859, Aimé Laussedat was one of the first to plot Paris by plane-table photogrammetry. Since then, the technique of photogrammetry has been refined, supported by technologic advances. Traditional assessment is to break down the dimensions into three planes (x - y , frontal elevation; y - z , side elevation; and x - z , plan view). This method tends to oversimplify an object as there is a considerable amount of information other than these projections. The development of image capture and analyses has been restricted due to technologic restrictions in both hardware and software. In recent years, the various techniques of capturing three dimensions have improved, in association with reduced costs of equipment and software, which makes the techniques affordable and usable by a wide variety of disciplines.

THE PRESENT

There is no doubt that 3D imaging is having a significant impact on everyday activities through the medical, retail, and entertainment industries. There has been no lack of ideas in the applications and

implementation of 3D imaging. However, researchers have been waiting for significant improvements in the development of easy-to-use, low-cost, high-resolution, non-life-threatening acquisition systems, suitable algorithms, and significant computer programming power. 3D imaging can generate a large volume of data that can take many hours to analyze, although processing times can be significantly reduced using multiple core processors and computer clusters. Nevertheless, these new imaging systems enable the option of recording and quantifying facial data and, with the advancement of computing technology, there is no doubt that processing times will decrease, allowing their routine use.

THE FUTURE

The drive over the next 10 years will be to develop a suite of commercially available software programs that will automatically register, landmark, compare, evaluate, and report surface changes using all the acquired facial data.

Automatic dynamic facial identification software has enormous potential not only in the security industry, but also in healthcare. Since it is possible to identify a single individual with a high degree of sensitivity and specificity, it will be possible to identify groups of individuals with similar facial morphologies and facial characteristics. Already it is possible to identify facial dysmorphology in static images,¹ and once large datasets have been accrued, dynamic images will facilitate the automatic diagnosis of various types of facial morphology, the best approach to intervention leading to a comparison of expected and achieved outcomes. In addition, epidemiologic facial morphology studies of parents and their children may provide some insight into the genetic and environment factors that may influence face shape.

The study of craniofacial dysmorphology has developed significantly in recent years, with a particular focus on craniofacial parameters in association with other common morphologic features such as head circumference, eye and ear measurements, nasolabial distance, hand measurements, and internipple distance.² Before we can achieve full automation of diagnostic systems, there is a considerable amount of groundwork that needs to be undertaken in attaining normalized data for different population groups, similar to epidemiologic studies in which two-dimensional data have been obtained but for future purposes 3D data will be required.² For instance, the face (eyes, nose, cheeks, lips, chin, and overall face) in static and dynamic modes (facial Action Units) needs to be fully characterized across the full range of variation with respect to age, gender, and ethnicity.

These data will be invaluable in establishing population-based norms for individuals attending a variety of healthcare clinics (e.g., orthodontists, maxillofacial surgeons for facial disharmony, and speech and language therapists). With the classification of facial features, genome-wide association studies can be undertaken to explore genotype–facial phenotype relationships. Some possible genotype–phenotype relationships are ready for further assessment (Table 19.1) and have been reviewed elsewhere.³

Genome-wide association studies are currently being conducted in centers around the world. Large cohort studies such as the Avon Longitudinal Study of Parents and Children (involving 5500 15-year-old children)¹⁴ has provided and will continue to provide an invaluable resource to explore genotype–facial phenotype associations.

In addition, dynamic 3D facial shape and texture databases will provide a unique resource, enabling the development of improved facial models for computer graphics, computer vision, and biomechanical engineering applications. A fully dynamic biomechanical talking head is often a goal for some researchers. This aim may be enhanced by recent advances in magnetic resonance imaging in which the orienta-

Table 19.1 Previous reports of genetic factors influencing face shape

Genetic factor	Effect
IIX MHC protein	Negative 2–4-fold reduction in gene expression in “long face” compared with “normal” facial form ⁴
6-Integrin expression	
Fibronectin	
Alpha-cardiac MHC	Positive 2–4-fold reduction in gene expression in “long face” compared with “normal” facial form ⁴
Perinatal MHC	
Developmental MHC	
Growth hormone gene receptor ⁵	Size and shape of the mandible and maxilla
Chromosome 12 ⁶	
Chromosome 10/11 ⁷	
Fibroblast growth factor signalling Fgfr2 and 3 ⁸	
Dix-2–3 ⁹	
Orthodentical-related homeobox	
Otx ¹⁰	
Pair-box Pax9 ¹¹	Facial prominence, facial asymmetry
Paired Homeobox	
Pitx/Ptx1/Brx2, Pitx2/Otix2/RIEG/Brx1 ¹²	
Basic helix–loop–helix Twist ¹³	

MHC, myosin heavy chain.

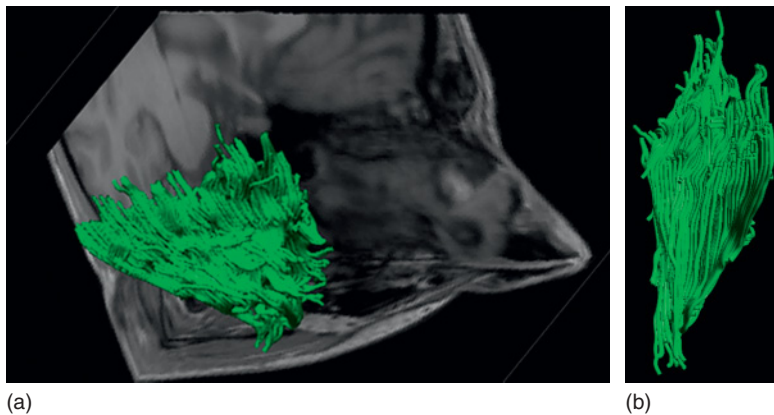


Figure 19.1 (a) The orientation of the muscle fibers for the temporalis muscle superimposed onto a structural magnetic resonance image. (b) The temporalis muscle seen from the posterior view.

tion of facial muscle fibers can be identified to facilitate the creation of an individualized biomechanical model of muscles in action and relaxation (Figure 19.1).

Leading on from the facial identification, facial gestures could be identified, facilitating the development of verbal/nonverbal communication technologies that might be of use in developing interactive communication and educational systems. For instance, a computer algorithm could recognize when the user was relaxed and enjoying the experience, or puzzled, tired, and angry!

3D imaging provides the opportunity to revalidate or refute controversial issues relating to the benefit of certain oral and facial healthcare interventions. For instance, do restricted airway resistance (large adenoids, tonsils, or asthma) and intraoral appliances (functional appliances for individuals with a retrognathic mandible) influence facial development? Previous studies have used two-dimensional assessment, but whole-face 3D assessment may yield different answers.

Rapid development in 3D imaging will provide opportunities for the research community to be creative in all disciplines and hopefully improve the quality of life for us all.

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Appendix 1: Sample of Informed Consent for Imaging Procedures

This is my consent for a cone beam computed tomography (CBCT) scan, as previously explained to me, to be made of my maxillofacial region involving the:

- a. ☐ Bottom jaw (mandible) region
- b. ☐ Top jaw (maxillary) region
- c. ☐ Combined top and bottom jaws
- d. ☐ Cranial base, face, and combined jaw region
- e. ☐ Jaw (temporomandibular) joint region

or other imaging procedure(s) deemed essential or advisable to obtain the following diagnostic information reasoned to be necessary to initiate or complete my treatment.

- a. maxillofacial pathology _____

- b. pre-treatment shape and size jaw bone evaluations

I understand that the purpose of the procedure is to diagnose and/or evaluate my oral and maxillofacial structures to obtain information that is not available clinically. I have been advised that if this information is not obtained, it will be more difficult to determine a pre-surgical treatment diagnosis and it will be more difficult to plan successful

- a. ☐ implant/prosthetic treatment
- b. ☐ orthodontic/orthognathic treatment
- c. ☐ incisional/excisional biopsy surgery

I have been informed of possible alternative methods of treatment, if any.

It was explained to me that there are certain inherent and potential risks from X-rays. The potential long-term risks to patients of this X-ray examination are uncertain, but they have never been associated

with any definite adverse effects. The amount of X-ray dose from a CBCT scan would be similar to the amount of exposure a person receives from living at sea level for six days. This is similar to the dose of two chest films. Hence, the risks in this specific instance are minimal.

No guarantee or assurance has been given to me that the proposed procedure will be definitive to my complete satisfaction. The procedure results are, however, expected to improve diagnosis, treatment planning or treatment outcomes.

I have had an opportunity to discuss and have made a full disclosure of my past medical and health history including any serious problems and/or injuries. This includes any past or present substance abuse.

Because successful treatment often depends on compliance with a doctor's instructions, I agree to cooperate completely with the recommendations of the doctor and his or her professional staff, realizing that any lack of same could result in a less than optimum result.

I certify that that I have had an opportunity to read and fully understand the terms and words within the above consent to the procedure and the explanation referred to or made, and that all blanks or statements requiring insertion or completion were filled in and inapplicable paragraphs, if any, were stricken before I signed. I also state that I read and write English.

Witness

Patient, Parent or Guardian

Date

Witness

Doctor or Professional Staff

Date

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